Innovative Infrastructure Solutions (2024) 9:147
https://doi.org/10.1007/s41062-024-01430-8

TECHNICAL PAPER

Effect of stabilizing subgrade layer using various additives on the flexible pavement design

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Received: 31 December 2023 / Accepted: 7 March 2024

Abstract

Soil stabilization involves enhancing the physical properties of soil to increase its stability, durability, and ability to support heavy loads, making it a crucial technique in civil engineering and construction. The process is used to reduce soil permeability and compressibility and increase its shear strength. To achieve this, various additives are used. This paper evaluates RoadCem (nanomaterial) and traditional additives such as cement, lime, and ashes materials such as rice husk ash (RHA) and fly ash (FA) as by-product materials in clayey soil stabilization. The used percentages of Lime were (2, 4, 6, and 8%), cement and RoadCem (3, 6, 9, and 12%), FA (3, 6, 9, 12, and 15%), and RHA (5, 10, 15, 20, and 25%) by dry weight of the tested soil. Various tests were used to examine and evaluate the physical and engineering characteristics of the treated soil, modified proctor, atterberg limits, free swelling (FS%), unconfined compressive strength (UCS), California bearing ratio (CBR), and resilient modulus (Mr) as well as microstructure tests [scanning electron microscopic (SEM)]. All admixtures were tested and subjected to two curing periods, 7 and 28 days. The results indicated that the optimum additives percentages were selected as 6% FA and 15% RHA activated by 6% lime and 6% for both RoadCem and cement. At these percentages, plasticity, FS%, and optimum moisture content (OMC) values were decreased. In contrast, maximum dry density (MDD), UCS, CBR%, and Mr values were increased. In addition, the correlation between Mr and both CBR and UCS was drawn. SEM results showed that major changes were observed in the microstructure of treated samples due to the forming of cementitious materials. The study evaluated the effect of subgrade stabilization on reducing base layer thickness under light, medium, and heavy expected traffic loads with an economic analysis to examine the benefits of subgrade stabilization. The cost analysis showed that the optimal economic additives were RoadCem and cement.

Keywords Clayey soil · RoadCem · Lime · Rice husk ash · Fly ash · Cement · Subgrade · Strength · Resilient modulus

Introduction and background

With the global expansion of highway networks, especially in agricultural regions, the use of clayey subgrade soil has become widespread. However, this soil type has inherent vulnerabilities that can result in engineering difficulties, such as deflections and cracks. To improve the performance of clayey subgrade soils, various approaches are employed, including soil replacement and soil stabilization techniques. Soil stabilization or modification can be accomplished through three primary methods: physical, physico-chemical (bituminous), and chemical stabilization [1, 2]. Physical or mechanical stabilization refers to the enhancement of soil properties by applying external energy. Physico-chemical stabilization involves the combination of bitumen with the soil, serving as a waterproofing agent. Chemical stabilization can be achieved by mechanically mixing the natural soil with a stabilizing material to create a uniform mixture or by adding the stabilizing material to an undisturbed soil deposit, allowing it to permeate through the soil voids and establish interaction [3].

The presence of poor engineering properties in soils often poses challenges during construction, leading to the

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Published online: 16 April 2024

necessity of soil stabilization to enhance their characteristics [4]. Soil stabilization aims to improve the geotechnical properties of soil such as shear strength, swelling and shrinkage characteristics, and bearing capacity. In most cases, the engineering properties of the stabilized soil improved depending on the stabilizer type, soil type, stabilizer amount, and curing conditions. Various additives and stabilizers (traditional stabilizers) can be used in improving soil characteristics as lime, cement, silica fume (SF), fly ash (FA), rice husk ash (RHA), ground granulated blast slag (GGBS) [5]. These additives are employed to improve the properties of less-desirable road soils. Their usage can enhance and regulate soil moisture content, increase cohesion among soil particles, and act as cementing and waterproofing agents [6]. Clay soils present a difficult problem in civil engineering projects, as they tend to expand when their moisture content rises [7].

Extensive research has been conducted on soil stabilization, exploring the use of different additives. In pavement construction, cement and lime stabilization are the commonly employed methods for stabilizing clay soils. While cement and lime stabilization can yield high strengths, there are instances where such strength levels may not be necessary. This justifies the exploration of more cost-effective additives that can modify soil properties. In addition, soil stabilization is considered a friendly environmental process as it uses a by-product and waste materials in soil modifications. Burnt ashes were examined to enhance the engineering properties of clayey soils [8–19]. Zimar et al. (2022) discussed the review of the usage of fly ashes in soil stabilization, it was noted that fly ashes are one of the major wastes generated from coal power plants, and they have a significant impact on the environment and use in the stabilization of different types of soils under different conditions [20]. Amhadi and Gabriel (2021) evaluated the use of cement and fly ash in the natural desert sand. The results indicated that by improving the sand layer with cement, the thickness of both the base and asphalt layers may be substantially reduced (50% for the asphalt and 25% for the base) for a net saving of approximately 25% of the cost of the road. Also, adding 7% fly ash enhanced the properties of the desert sand and met the required strength [21]. Several studies used SF and GGBS in soil stabilization, and the results indicated significant improvement in soil properties [22–26]. These additives can be used individually and in combination with more materials. SF activated with lime was evaluated in enhancing clayey soil characteristics, and the results showed better properties [27, 28].

Various materials were used in both asphalt and concrete mixes as environmentally friendly materials Bameri et al. (2022) evaluated the mechanical and durability properties of binary and ternary concrete mixtures containing SF, waste glass powder (WGP), and GGBS. The results of their research showed that combining these additives significantly improves the properties of the concrete mixtures [29]. Recently, modern techniques and additives have been used in construction projects such as nano-materials and RoadCem. Oltulu et al. (2011) and Qing et al. (2005) evaluated the use of nano-silica (NS) in concrete mixes [30, 31], and Mostafa et al. (2016) used it as a stabilizer in clayey soil improvement. The findings showed that the major effect of NS was found and it improved the mechanical properties of the tested soil. The RoadCem is a product manufactured by PowerCem Technologies, which mentions economic and environmental advantages in both the reduction of the construction cost and in the environmental impacts [32]. It is a by-product additive based on nanotechnology, which contains synthetic zeolites and alkaline earth metals in its composition [33]. Through chemical reactions with the soil, it modifies its mineralogy, resulting in a strong, durable, and fibrous crystalline structure. Additionally, it changes the dynamics and chemistry of cement hydration, improving the crystallization process and the formation of crystalline structures with longer needles [34]. This crystalline framework reinforces and increases the resistance and flexibility of the stabilized layers of a floor, as well as improves the overall performance of cement in paving [32]. In another context, there is the determination of the mechanical behavior of stabilized soils, through tests. Previous research studied the use of RoadCem in soil stabilization with and without different additives [35–37].

Based on the previous introduction and review, it was observed that various traditional and modern materials are introduced to strengthen the clay soils and minimize the use of natural resources. However, few studies were conducted on clay soil stabilization using RoadCem mixtures. This paper introduces the analysis of using RoadCem and traditional materials in clayey soil stabilization. As well as it aims to evaluate the use of these additives in the design of flexible pavement. Bhardwaj and Sharma (2021) studied the effect of using waste foundry sand, molasses, and lime on the design of subgrade thickness for flexible pavements [38]. It was investigated that the smaller amounts of lime with low costs can introduce stronger subgrade material. Suitable results were achieved with only 3% lime, 20% WFS, and 10% molasses, which were needed for the optimum stabilization of clayey soil. The pavement thickness was reduced using these additives based on the CBR values and using IIT pave software.

Objectives of the study

The objectives of this study can be summarized as follows:

- Investigate the effect of using traditional additives cement, lime, FA, and RHA (with and without lime), and nano-cementitious material (RoadCem) on the physical and mechanical properties of clay-stabilized soil.

- Determine the optimum percentages of individuals and combinations of the used additives using various engineering tests.
- Conducting the microstructure test (SEM) to analyze the chemical reactions between the soil particles and various additives.
- Based on the optimum percentage outcomes, extra tests and analyses were conducted to evaluate the stabilized pavement section, economically, and performance.

Table 1 Physical properties of the tested soil

Physical properties	Test result
Specific gravity	2.48
Liquid limit (L.L)	72.00
Plastic limit (P.L)	38.90
Plasticity index(P.I)	33.10
Maximum dry density (MDD), gm/cm^3	1.55
Optimum moisture content (OMC) %	18.9
AASHTO soil classification	A-7-5

Materials and testing

Tested soil

Table 1 presents the physical properties of the used soil obtained from Monofia, Egypt. Figure 1 shows its grain size distribution.

Additives

The used additives are cement, lime, rice husk ash (RHA), fly ash (FA), and RoadCem. Table 2 shows the chemical composition of the used additives. The treated soil was blended with one or more additives with different percentages by the dry weight of the tested soil. The tried percentages were lime (2,4,6 and 8%), cement and RoadCem (3,6,9, and 12%), FA (3,6,9,12, and 15%), and RHA (5,10,15,20,

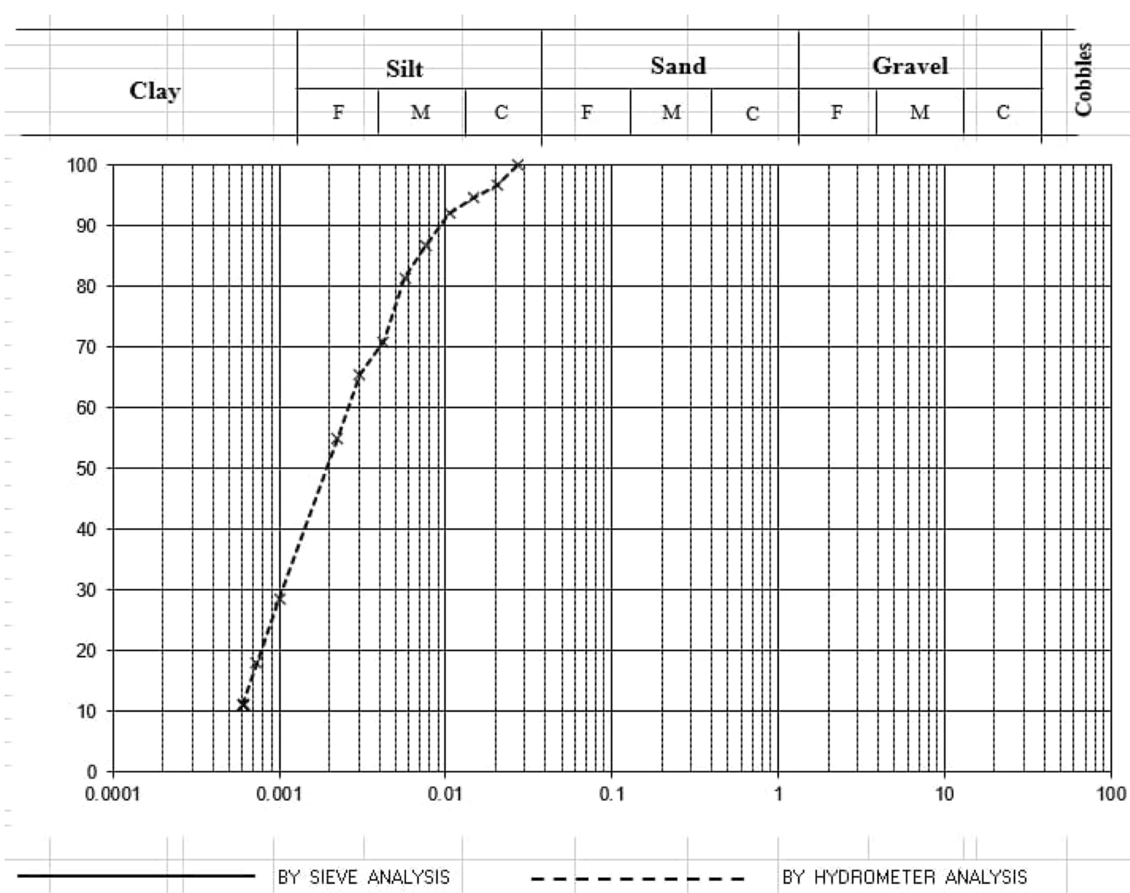

Fig. 1 Grain size distribution of the tested soil

Table 2 Chemical composition of the used additives

Component	Percentage %				
	Cement	Lime	RHA	FA	RoadCem
SiO_2 (silicon dioxide)	20.93	1.92	72.34	61–64.29	21.4
AL_2O_3 (aluminum oxide)	4.53	0.15	4.43	61.6–27.04	1.99
Fe_2O_3 (iron oxide)	3.45	0.62	1.21	3.09–3.86	0.62
CaO (calcium oxide)	65.11	50.71	1.54	1.02–3.39	47.3
MgO (magnesium oxide)	1.35	0.31	0.98	0.5–1.58	4.1
SO_3 (sulfur trioxide)	2.71	12.62	–	Up–0.07	–
TiO_2 (titanium oxide)	–	0.03	–	1.25–1.69	–
MnO	–	0.01	–	Up to 0.05	–
K_2O (potassium oxide)	0.11	0.24	3.54	0.08–1.83	7.11
Na_2O (sodium carbonate)	0.42	1.71	0.75	0.28–0.48	–
LoI (loss-on-ignition)	0.65	31.21	15.21	0.2–0.85	–
+Others	–	20.01(P2O5)	–	–	–

Data supplied by Egyptian Mineral Resources Authority

and 25%). RHA and FA percentages were blended with 6% lime as an activator to determine the optimum combination of both RHA-Lime and FA-Lime.

Tests

Several mineralogical and engineering tests were carried out on conventional and treated soil subjected to two curing periods (7 and 28 days), these tests are:

Compaction (modified proctor) test

The modified proctor test was conducted according to ASTM D1557 [39] to determine the maximum dry density (MDD) and the optimum moisture content (OMC) for control and treated mixes. The OMC is used in preparing samples for UCS, CBR, FS%, and resilient modulus (Mr) tests.

Atterberg limits (plasticity) test

In compliance with ASTM D 4318—standard test method for liquid limit (L.L), plastic limit (P.L), and plasticity index (P.I) of soils, the atterberg limits test was performed [40]. Atterberg limit (consistency) tests are performed on the raw materials of the tested soil. The tests are carried out on the test soil which is mixed with various additives with different percentages as explained above.

Free swelling (FS) test

FS% is defined as the increase in the volume of the soil from a loose dry powder after pouring into water and expressed as a percentage of the original volume [41]. About 50 g of the test soil which passed through sieve no.40 is oven dried at 50 °C. After that, the soil sample is placed in a 25 ml cylinder up to the 10 ml mark without any shaking down or compaction. Then, place 50 ml of distilled water in a 50 mm diameter measuring cylinder. The 10 ml soil sample is placed slowly into the water, then, leaves the soil in water for at least half an hour to settle the soil particles. The volume of settled solids is then determined (Vml). Finally, FS% can be calculated using Eq. (1).

$$FS\% = \frac{V - 10}{10} * 100 \tag{1}$$

California bearing ratio (CBR%) test

This test was conducted according to AASHTO T193-99 [43]. The CBR test, originally developed by the California State Highway Department in the United States, is a penetration test performed under both unsoaked and soaked conditions. This test is used in the evaluation of the bearing capacity of the test soil such as subgrade, subbase, and base soils for flexible pavement design. The CBR test can be implemented on natural or compacted soils and the results obtained are compared with the curves of the standard test of the standard soil. The tested samples in this study are tested in soaked conditions.

Unconfined compressive strength (UCS) test

According to ASTM D 2166 [43], the unconfined compressive strength (UCS) was conducted for treated and untreated soil. UCS test is widely used to assess the strength of stabilized soil and is recommended for determining the optimal amount of additives for soil stabilization [44]. The OMC is used in this research to obtain the MDD for each mixture. The mold dimensions are (50 mm diameter and 100 mm height). All samples are tested in a universal test machine with a loading rate of 0.85 mm/min, to allow the specimen to fail in about 5–6 min until failure.

Resilient modulus (Mr) test

Mr test was conducted according to AASHTO TP46 [45]. Mr is usually determined in a repeated triaxial test wherein confining pressure and deviator stress can be controlled. The test is usually carried out by several stress repetitions over a range of deviator stress levels and confining pressure levels representing variation in-depth or location from the point of application of load. The Mr was determined using Eq. (2):

$$\mathrm{Mr} = \sigma d / \varepsilon r \quad (2)$$

where, σd is the axial deviator stress, and εr is the resilient axial strain $\sigma d = P/A$ where P is the applied load and A is the cross sectional area of the specimen $\varepsilon r = \Delta L/L$ where ΔL is the recoverable axial deformation and L is the original length of the specimen.

The determination of the resilient modulus (Mr) through testing is an advanced method used to assess the properties of pavement materials. However, conducting Mr test requires skilled technicians and expensive equipment that are not readily available in basic laboratories. Consequently, many researchers and design engineers rely on correlations between Mr and other strength parameters or soil index properties to estimate Mr values for subgrade materials.

Scanning electron microscopy (SEM) test

SEM is a tool and a common instrument in materials analysis and characterization. It is preferred to the optical microscope when higher magnification or an increased depth of field is needed, or when some sort of elemental or compositional analysis is required. SEM is used to generate images of the surface and the subsurface of a specimen at magnifications in the range of 14–1,000,000×. It can be used to examine the microstructure of specimens and to determine particle crystallinity. SEM may also be used to characterize and identify particular phases and their shape and forms. It has the advantage of giving three-dimensional images of superior depth of focus and resolution capabilities compared to optical micrographs.

Results and discussions

Compaction (modified proctor) test results

Figure 2 displays the compaction characteristics, as indicated by MDD and OMC of conventional and treated soil. Figure 2a shows the effect of adding lime only to the clayey soil. The results indicated that the presence of lime increased both MDD and OMC dramatically, these findings agreed with several previous studies [46, 47]. Ashes materials (FA and RHA) with and without lime changed both MDD and OMC. FA increased the MDD and decreased the OMC; while, RHA increased both MDD and OMC compared to the control mixture as shown in Fig. 2b, c which agrees with the findings by Aparna Roy (2014) [48]. Figure 2d shows the compaction characteristics for cement and RoadCem, the results demonstrated that the MDD and OMC generally increased with an increase in additives percentage. The values for cement additive were higher than those of RoadCem for both MDD and OMC. Adding additives reduces the quantity of free silt and clay fraction and forms coarser materials with larger surface areas, which require more water for compaction.

Plasticity test results

Figure 3 exhibits the results of P.I for control and modified mixtures for both 7 and 28 days. P.I dramatically decreased by increasing the curing period for all mixtures. Adding additives to clayey soil changed soil classification. For example, (L.L, and P.I) of the control mixture and soil treated with (6% + 15%RHA) were (72, 33.1%) and (58, 20.7%) respectively, and the control soil was classified as CH (high plasticity clay) changed to MH after adding 6% lime + 15% RHA according to plasticity chart. MH soil is better than CH in use in civil engineering applications. The change may be due to the flocculation that happened in treated soil which decreases the water absorption and lowers the liquid limit. These results agree with the findings of previous research [49–51]. This enhancement in plasticity will be reflected in the design by reducing the pavement section due to the improvement in subgrade engineering properties. The curing time plays a major role in reducing the plasticity of the treated admixtures.

Free swelling (FS%) test results

The values of FS% for conventional and treated mixtures are shown in Fig. 4 for 7 and 28 days. The selected expansive soil demonstrates a decrease in swelling tendency when additives blended, such as lime, FA, RHA, Cement, and RoadCem alone or a combination of lime with FA and RHA. The curing time has a major role in reducing the FS% values. The results showed a clear reduction in FS% values when FA or RHA is introduced to the test soil. Specifically, the FS% percentage decreases by 26% and 25% with the addition of FA and RHA alone respectively after 28 days, compared to the control mixture.

The observed decrease in FS% is attributed to the presence of divalent and trivalent cations (such as $Ca2+$, $Al3+$,

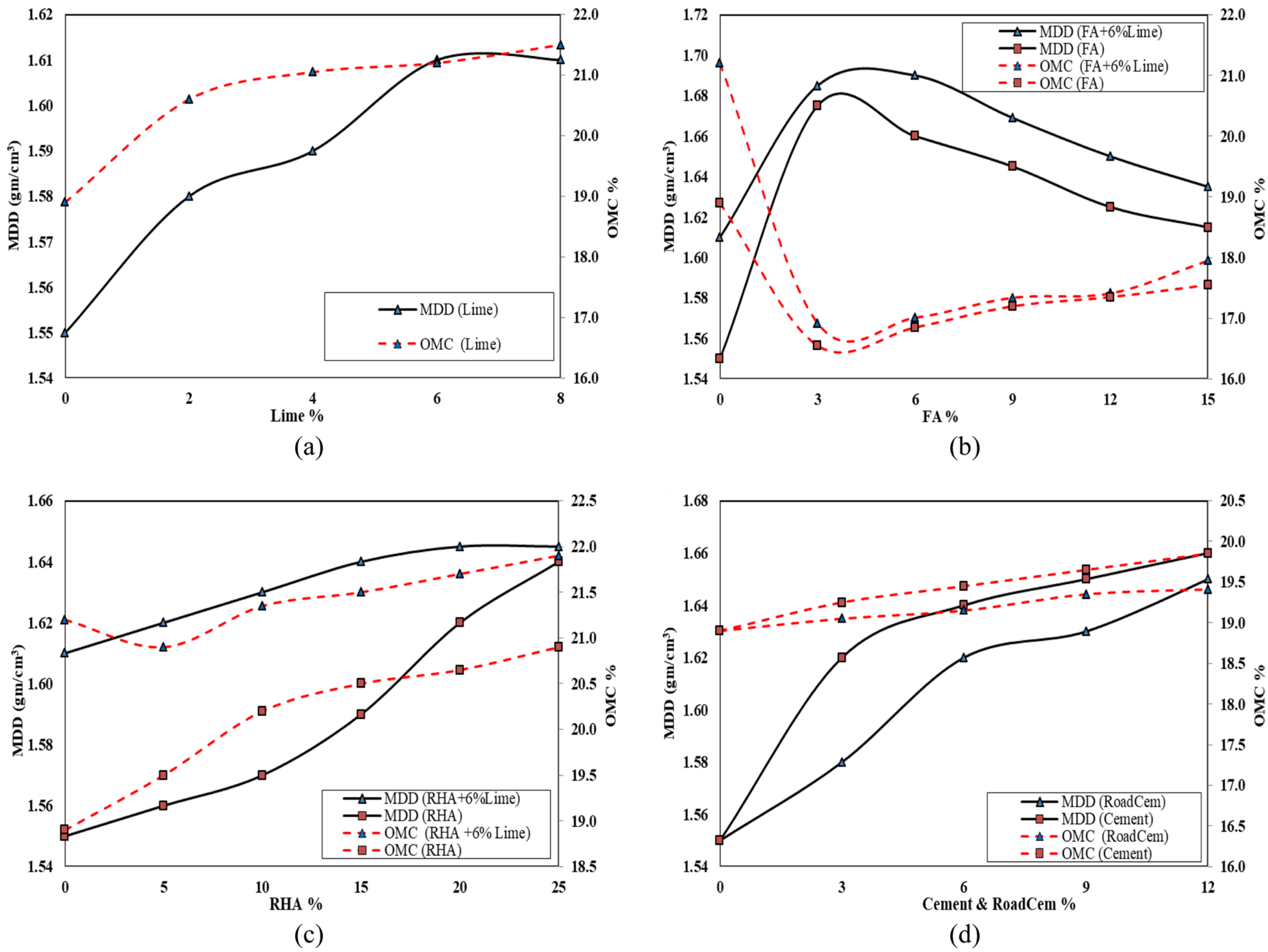

Fig. 2 Effect of adding various additives on MDD and OMC, **a** lime, **b** FA with and without lime, **c** RHA with and without lime, **d** cement and RoadCem

and Fe3 +), which promote the flocculation of clay particles, leading to an increase in particle size and a reduction in the soil sample's surface area and water affinity. These results are aligned with the findings of Indiramma et al.(2019) and Zimar et al. (2022) [20, 52]. Also, the findings of soil treated with cement and RoadCem showed a reduction in FS% values, and the results of the two additives were almost similar.

Unconfined compressive strength (UCS) test results

Figure 5 depicts the influence of lime, ashes materials (FA and RHA) with and without lime, cement, and RoadCem on the UCS of the tested soil. The effect of curing time on UCS values was also examined and analyzed. The results demonstrate that the UCS for soil treated with cement and RoadCem was higher than the other additives. UCS for control soil was 68 psi, which is a small value. Adding 6% lime increased this value to (127,154) psi after (7, and 28) days, respectively, by enhancement of 87 and 126%. ashes materials (FA and RHA) introduced higher values of the UCS compared to the control mixture. Soil treated with 6% FA recorded a UCS of (189,223) psi after (7, and 28) days while adding 15% RHA to control soil increased the UCS value to (107,159) psi after (7, and,28) days. Also, the combinations of additives (ashes + lime) increase the UCS values. For example, the combinations of (6% lime + 15% RHA) and (6% lime + 6% FA) increased the UCS values to (160,195) and (229,272) after (7, and 28) days, respectively. However, lime alone or the combinations of lime and ashes materials enhanced the unconfined compressive strength of the treated soil, and this enhancement varies by the variation in additives percentages. In contrast, cement and RoadCem have the highest effect on the UCS values compared to the traditional additives. Adding 6% Cement changed the UCS from 68 to 235 and 319 psi after (7, and 28) days. Also, the soil treated with 6% RoadCem has UCS values of 270 and 549 psi after (7, and 28) days which was greater than cement values. This increase in UCS is considered an indicator of

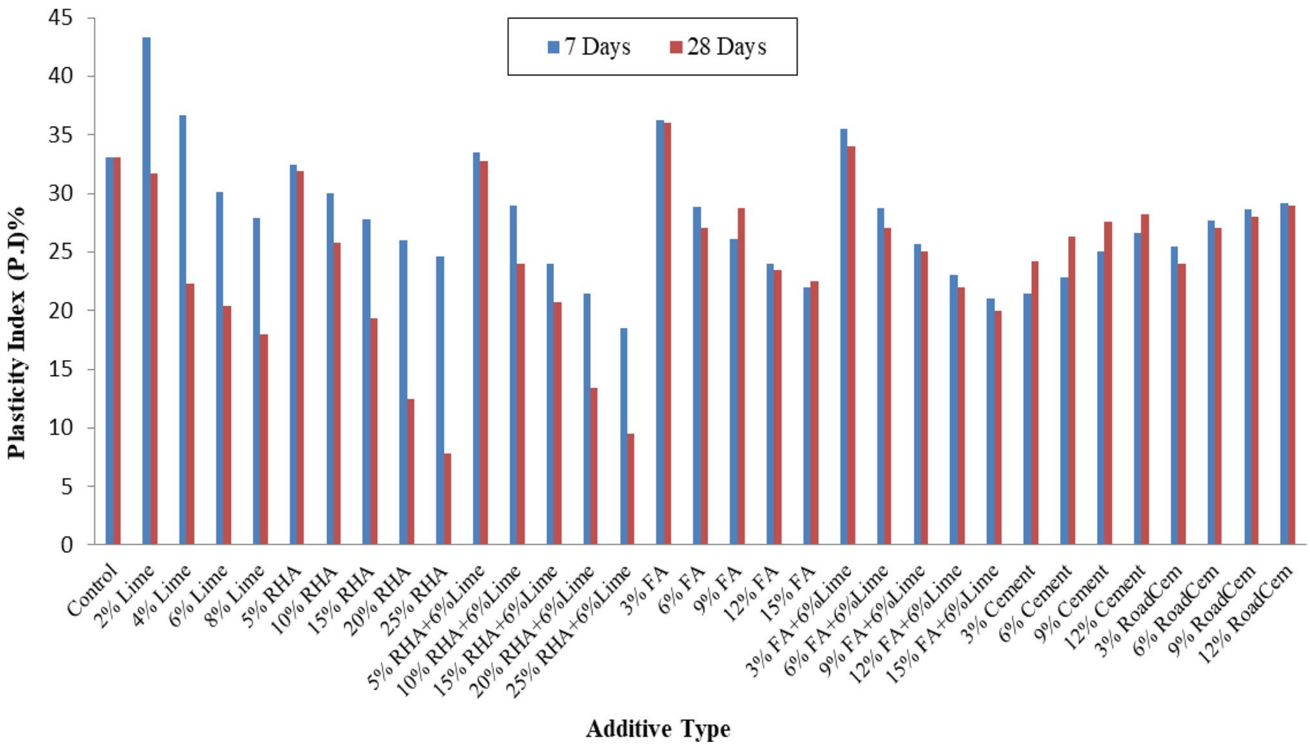

Fig. 3 Effect of adding various additives on plasticity after 7 and 28 days

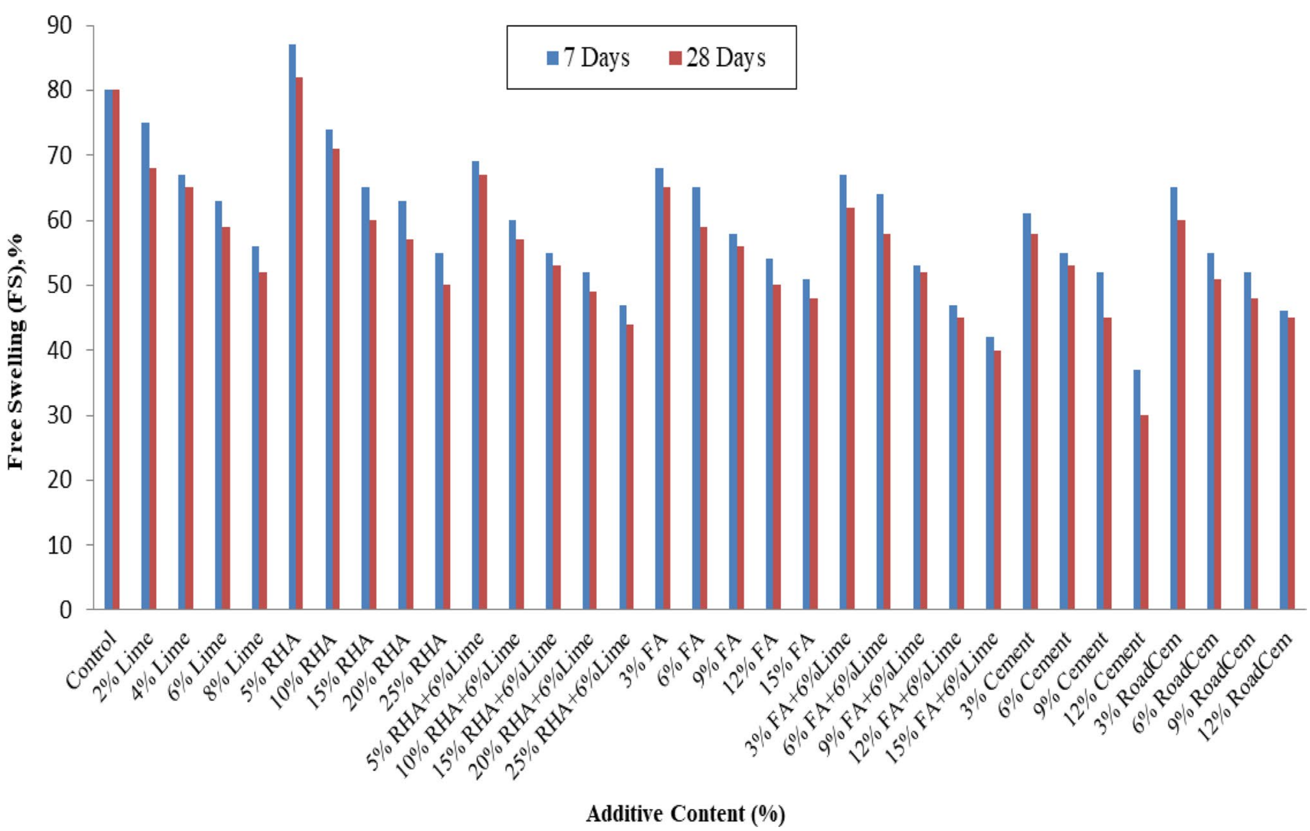

Fig. 4 Effect of adding various additives on FS % after 7 and 28 days

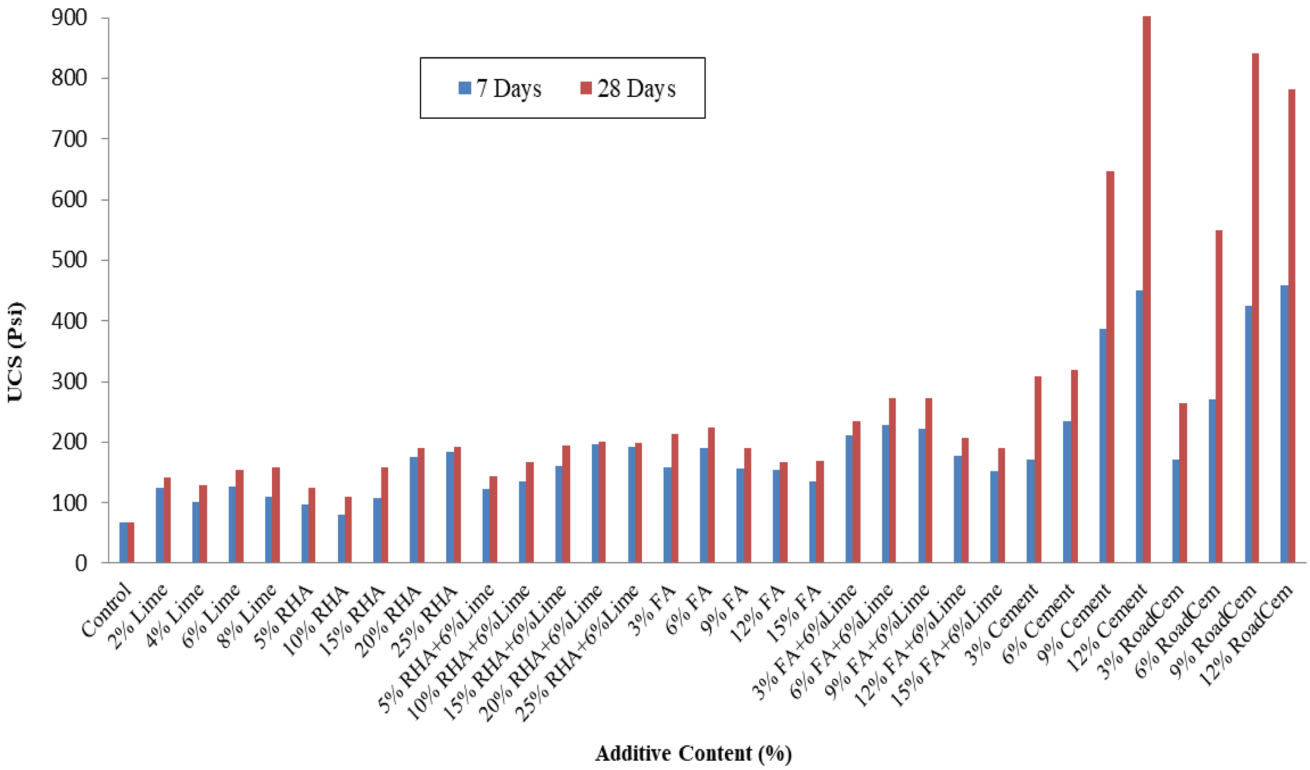

Fig. 5 Effect of adding various additives on UCS after 7 and 28 days

enhancement of pavement section performance containing stabilized soil, which can be subject to various traffic and environmental conditions. Therefore, evaluating the performance of the stabilized pavement section treated with these materials is essential. In this study, the UCS test was used as a guide to select the optimum additives to carry out extra tests and analyze the benefits of using these materials to enhance the performance of subgrade pavement sections. Amhadi and Gabriel (2021) [21] concluded that adding 7% fly ash to the sand soil increased the UCS and bearing capacity after the curing period which was similar to the findings of the current study. The outcomes of Leonardo Behak, (2017) [53] noted that the combination of lime and RHA increased and enhanced the strength of the treated soil which agrees with the results of the current study.

Optimum additives determination

Based on the previous results, compaction, plasticity, free swelling, and UCS test results at selected percentages of additives are discussed in this section. Table 3 shows the properties of untreated and treated mixtures at the optimum percentages of the used additives, which meet the required engineering properties, the reduction in plasticity and swelling as well as the increase in the soil strength. The selected additives are 6% cement, 6% RoadCem, and the combinations of (6% lime + 6%FA) and (6% lime + 15%RHA).

California bearing ratio (CBR) test results

In this study, the CBR test was conducted under soaked conditions, and the corresponding CBR values for the various additives (lime, FA, RHA, cement, and RoadCem) are shown in Fig. 6. The results demonstrate a significant influence of the additives on the CBR values. The untreated mixture has a small value of CBR (2.66%), which indicates that this soil needs improvement. The results of the selected optimum percentages indicated that a major effect occurred after adding FA and RHA activated by Lime on CBR values. Adding 6% FA + 6% Lime changes the CBR value from 2.66% to 14.22% with an enhancement of 435%. Similarly, incorporating a combination of lime and RHA had a significant impact on increasing the CBR values. Treating the conventional mixture with (15% RHA + 6%Lime) increased the CBR to 12.52% with an improvement of 371%. In contrast, the results of mixtures treated with both 6% Cement and 6% RoadCem record the highest values of CBR (27.02 and 32.71%). Although some studies noted that the CBR test was not significant in the case of cement stabilization, (especially, using high percentages of cement), thus, in this study, low percentages were selected, and the CBR procedure was considered.

Resilient modulus (Mr) test results

Figure 7 shows the variation in Mr values for control and treated mixtures at optimum percentages (5 mixtures). Mr strongly increased by treating clayey soil using ashes materials (FA and RHA) activated by lime and cementitious materials (cement and RoadCem). The highest value was found at 6% RoadCem, which increased from 6020 to 20,620 psi with an enhancement of 243%. In addition, treating the soil with (6% lime + 6%FA) and 6% cement changed the Mr values to 17,475 and 19,223, respectively. The lowest increase was found at 6% lime + 15% RHA, which slightly increased to 6945 psi. CBR and Mr are important parameters used in pavement design, and the enhancement of these values will enhance the pavement section performance. Therefore, the correlation between these parameters and their effect on pavement sections was studied in this paper.

Table 3 Mixtures properties at optimum percentages of the used additives

Mixture properties	Control	6% lime + 15% RHA	6% lime + 6% FA	6% Cement	6% RoadCem
MDD gm/cm^3	1.55	1.64	1.69	1.64	1.62
OMC %	21.20	21.50	17.01	19.45	19.15
Plasticity index (P.I) %, 28 days	33.10	20.70	27.00	26.30	27.00
FS%, 28 days	80.0	60.0	59.0	53.0	51.0
UCS (Psi)					
7 days	68	160	229	235	270
28 days	68	195	272	319	549

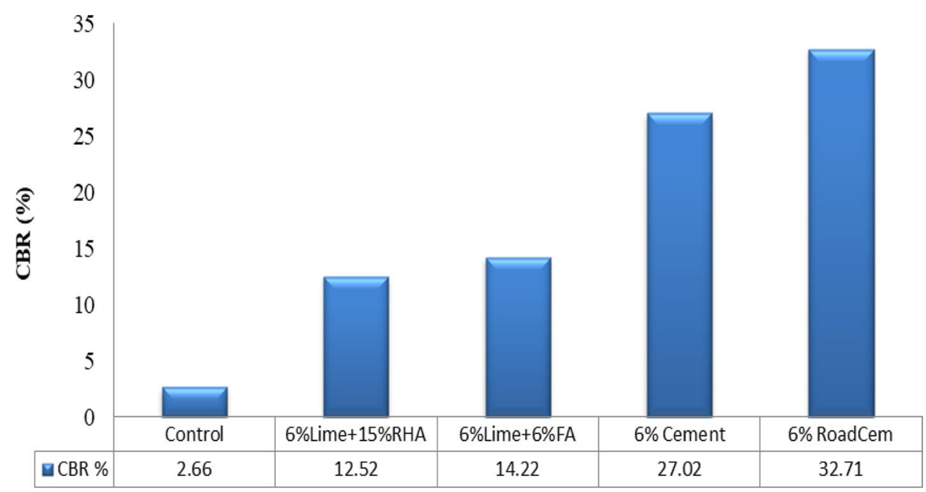

Fig. 6 Effect of adding various additives on the CBR%

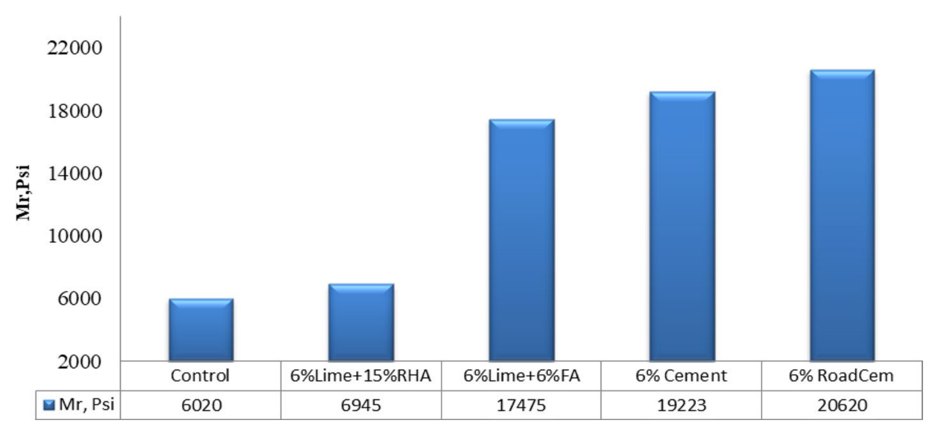

Fig. 7 Resilient modulus (M_r) for control and treated mixtures

Mr and CBR correlation

Mr is the main parameter used in characterizing subgrade soil and it is essential for pavement design of both flexible and rigid pavements [54]. The AASHTO 1993 design guide [55] for flexible pavement recommends the use of Mr for characterizing subgrade, subbase, and base soils, and this property is considered an input used in the mechanistic analysis of multi-layered systems. The Egyptian Code of Practice for Urban and Rural Roads (ECPURR) adopted Eqs. (3) and (4) to predict the Mr based on the measured CBR values of subgrade materials [56]. Equation (4) is updated to Eq. (5) based on measured CBR values of local base and subbase materials used in pavement construction in Egypt [57, 58]. Mechanistic-empirical design guides implemented in the AASHTO pavement M-E design use some of these correlations to estimate Mr values [59, 60].

$$\text{Mr (psi)} = 1500 \times \text{CBR, for CBR} < 10\% \quad (3)$$

$$\text{Mr (psi)} = 3000 \times \text{CBR}^{0.65}\text{, for CBR} \geq 10\% \quad (4)$$

$$\text{Mr (psi)} = 4920 \times \text{CBR}^{0.48}\text{, for CBR} \geq 10\% \quad (5)$$

In this study, the correlation between Mr and CBR values was examined as shown in Fig. 8. The correlation was conducted using five mixes and it showed that Mr was increased by the increase of CBR values with $R^2 = 0.75$. The relation is displayed in Eq. (6).

$$\text{Mr (psi)} = 506.7 \times \text{CBR} + 5024.20 \quad (6)$$

Mr and UCS correlation

The relationship between Mr and UCS is drawn in Fig. 9. The results indicated that the increase in UCS resulted in an increase in Mr. The relation can be formed in Eq. (7) with $R^2 = 0.86$.

$$\text{Mr (psi)} = 81.113 \times \text{UCS (Psi)} - 1549.5 \quad (7)$$

Effect of subgrade stabilization on flexible pavement design

All over the world, the common type of pavement is flexible pavement. Therefore, in this research, the effect of stabilizing the subgrade layer using various types of additives was examined. Table 4 shows assumed data used in the design of the flexible pavement section as an example. The pavement section was solved using the AASHTO–empirical guide method [55]. Three pavement sections were evaluated, section (I), section (II), and section (III) to simulate light, medium and heavy traffic, respectively. The analysis was conducted to determine the asphalt layer structural number (SN_1) to determine the asphalt layer thickness and the total structural number of pavement layers (SN_t) to calculate base layer thickness as shown in Table 5. Figure 10a shows the control section which consists of base and asphalt layers resting on a natural subgrade layer, and its layers varied according to section type. In contrast, Fig. 10b shows the pavement section containing a treated subgrade layer using various additives, and pavement thicknesses were changed by changing the section and stabilizer type. In the case of light traffic, the pavement section consists of one asphalt layer (6 cm), and in the case of medium traffic, the asphalt layer thickness was 11 cm (5 cm wearing surface + 6 cm binder layer) as in the case of heavy traffic where the asphalt

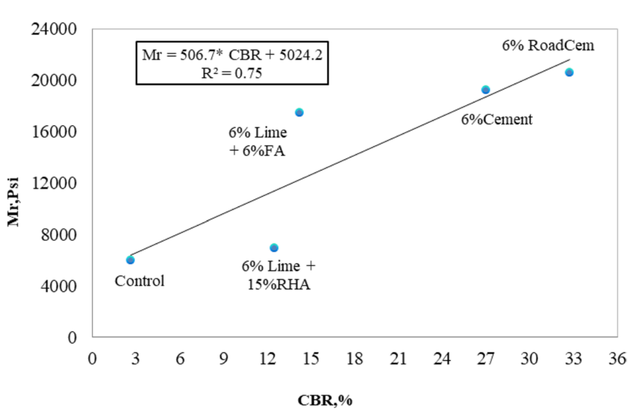

Fig. 8 Correlation between Mr and CBR for stabilized mixtures

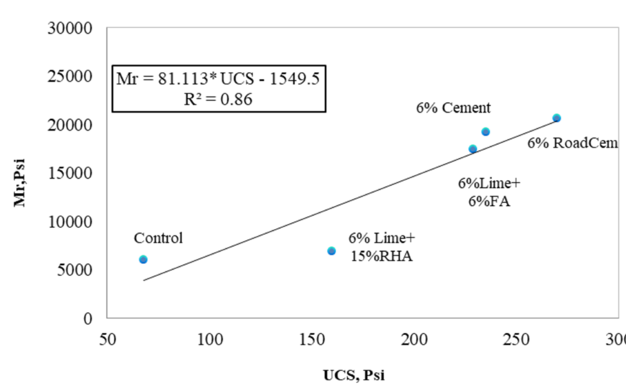

Fig. 9 Correlation between Mr and UCS for stabilized mixtures, (7 days)

Table 4 Flexible pavement design (input data)

Design parameter	Pavement section type		
	Section I (light traffic)	Section II (medium traffic)	Section III (heavy traffic)
Equivalent single axle load, ESAL	50,000	1×10^6	5×10^6
Mr of asphalt layer		400,000 Psi	
Asphalt layer coefficient, a_1		0.42	
CBR of base layer,%		80.0	
Mr of base layer, Psi (from Eq. 4)		40,313	
Layer coefficient of base layer, a_2		0.132	
Overall standard deviation, S_o		0.45	
Reliability, *R*%	80	85	90
Initial seveciability, *P*i		4.50	
Terminal seveciability, *P*t	1.50	2.0	2.50
ΔPSI = *P*i − *P*t	3.0	2.50	2.0
Drainage coefficient for base layer, m^2		1.0	
Measured subgrade (untreated soil) CBR %		2.66	
Measured subgrade (untreated soil) Mr, Psi		6020	

layer was 15 cm (2 wearing surface of 5 cm + 5 cm binder). The trial-stabilized layer in all sections and additives was 15 cm which reduced the required base thickness in different sections as presented in Table 5 which represents the summary of the design of the pavement section including a 15 cm stabilized layer. The layer coefficient for the stabilized layer (ai) can be determined based on Eq. (8) [61].

$$\text{Mr (psi)} = 30000 \times \left(a_i/0.14\right) \tag{8}$$

Figure 11 shows the reduction in base thickness (RBT) due to subgrade stabilization. Treating a 15 cm subgrade layer using various additives reduced the required thickness of the base layer, and it varies according to additive and section type. The maximum reduction occurs in the case of RoadCem by 52.4, 35, and 26.83% for light, medium, and heavy traffic conditions, respectively. While the lower reduction was found at 6% lime + 15% RHA. One of the benefits of improving the subgrade layer is preserving the natural sources of aggregates and reducing the overall pavement section cost. The results were similar to the findings provided by Bhardwaj and Sharma (2021) [38].

Cost analysis of treated and untreated flexible pavement section

The results indicated that treating 15 cm of the subgrade layer reduced the required base layer thickness using ashes materials activated with lime and cementitious materials, keeping the total structure number constant. To evaluate the benefits of soil stabilization in the pavement section, the total estimated cost of 1 m^2 (materials, operations, transportation, mixing, compaction, etc…) was calculated including untreated and treated subgrade for the three traffic conditions as presented in Table 5 and based on the cost assumption presented in Table 6. Figure 12 shows the percentage of the total estimated cost compared to the control section cost (estimated cost baseline) cost analysis concluded that the minimum cost occurred using cement and RoadCem which compared to control and combinations of (RHA and FA) with lime. The maximum reduction in cost due to subgrade stabilization occurred in the case of light traffic, which concluded that soil stabilization is effective in the case of light traffic compared to medium and heavy traffic.

Scanning electron microscopy (SEM) test results

Figure 13 shows major changes in specimens under SEM. Referring to Fig. 13a, the soil particles dispread under the SEM device and leaves voids in the soil structure, as spread spots without any connection. On the other hand, by adding additives to the control specimen and letting it cure for 7 and 28 days, the shape and structure of the treated soil changed. For example, see Fig. 13b, d, e for the flocculation and agglomeration of connected particles. This connection makes particles stronger than in the control specimen. The changes occurred due to the formation of calcium silicate hydrate (C–S–H). This component seems a group of lines as needles connecting soil particles and producing high strength and resistance forces under loads. The formation of C–S–H is the reason for the strengthening of treated specimens. The formation of C–S–H in the case of 6% lime + 15% RHA is smaller than other additives which

Table 5 Flexible pavement design of untreated and treated sections

Design parameters / Section type		SN_1 for asphalt layer	Req. asp-galt thick., cm	SN_t	Stabilized layer thick-ness, cm	Stabilized layer coefficient, a3 (based on Eq. 7)	Required base layer thickness, cm	Reduction in base thickness, cm	Reduction in base thickness (%)	Total esti-mated cost L.E/m^2	Estimated cost(%)
Section (I), light traffic	Control				–	–	21.0	0.0	0.0	410	100
	6%Lime + 15% RHA					0.032	17.0	4.0	19.0	477	116.34
	6%Lime + 6% FA	1.0	6.0	2.07	15.0	0.082	11.50	9.50	45.24	499	121.71
	6% Cement					0.09	10.50	10.50	50.0	382	93.17
	6% RoadCem					0.096	10.0	11.0	52.40	380	92.68
Section (II), medium traffic	Control				–	–	30.0	0.0	0.0	645	100
	6%Lime + 15% RHA					0.032	27.0	3.0	10.0	717	111.16
	6%Lime + 6%FA	1.80	11.0	3.38	15.0	0.082	21.0	9.0	30.0	737	114.26
	6% Cement					0.09	20.0	10.0	33.33	620	96.12
	6% RoadCem					0.096	19.50	10.50	35.0	617	95.66
Section (III), heavy traffic	Control				–	–	41.0	0.0	0.0	880	100
	6%Lime + 15% RHA				0	0.032	38.0	3.0	7.32	950	107.95
	6%Lime + 6%FA	2.48	15.0	4.62	15	0.082	32.0	9.0	21.95	972	110.45
	6% Cement					0.09	31.0	10.0	24.39	855	97.16
	6% RoadCem					0.096	30.0	11.0	26.83	850	96.60

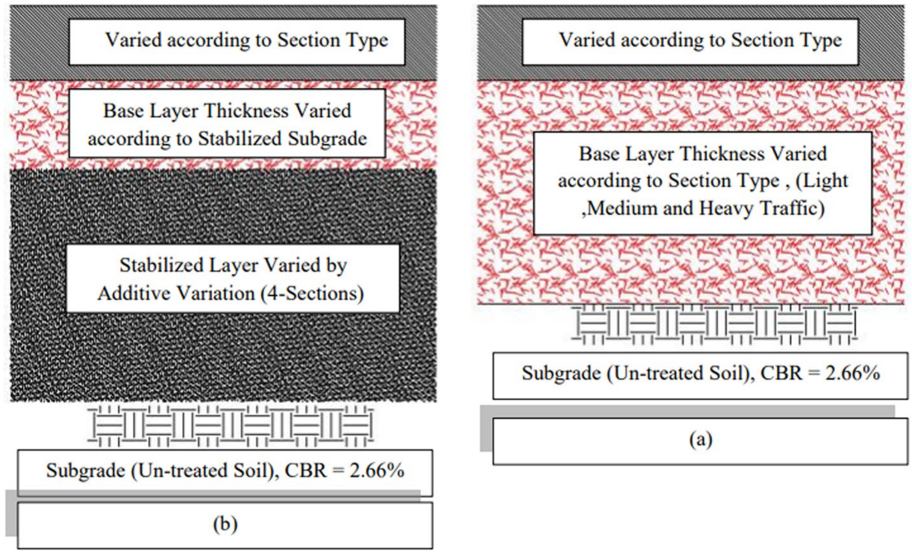

Fig. 10 Pavement section, **a** untreated section, **b** section with stabilized layer (treated section)

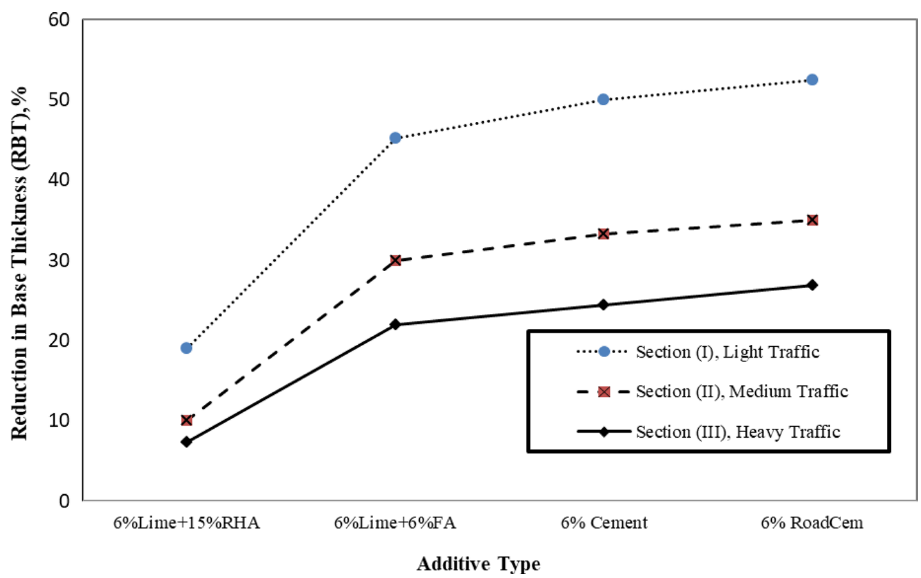

Fig. 11 Reduction in base thickness (RBT) due to subgrade stabilization

Table 6 Cost assumptions used in cost analysis

Item	Cost	Item	Cost
Grading and leveling the subgrade layer	15 LE/m^2	Construct 1 m^2 of tack coat layer including the total cost	20 LE/m^2
Construct 1 m^2 of the base layer with a thickness of 20 cm including the total cost	110 LE/m^2	Lime (raw material)	1500 LE/Ton
Construct 1m^2 of binder asphalt layer with a thickness of 6 cm including the total cost	200 LE/m^2	RHA (raw material) including burning and preparation	1800 LE/Ton
Construct 1 m^2 of binder asphalt layer with a thickness of 5 cm including the total cost	160 LE/m^2	Fly ash (raw material)	7800 LE/Ton
Construct 1 m^2 of wearing asphalt layer with a thickness of 6 cm including the total cost	240 LE/m^2	Cement (raw material)	2000 LE/Ton
Construct 1 m^2 of wearing asphalt layer with a thickness of 5 cm including the total cost	200 LE/m^2	RoadCem (raw material)	2100 LE/Ton
Construct 1m^2 of prime coat layer including the total cost	40 LE/m^2		

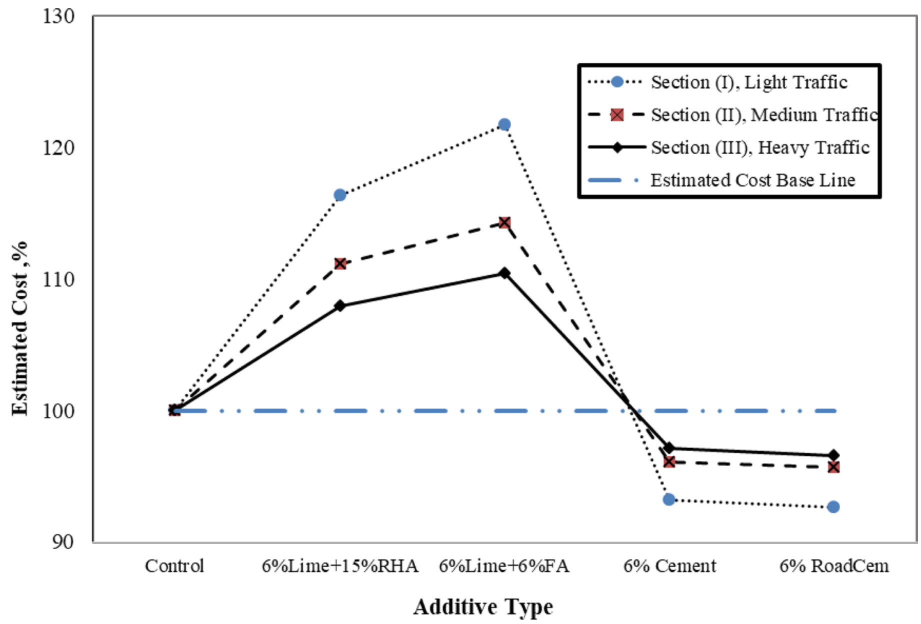

Fig. 12 Total estimated cost of pavement sections (untreated and treated subgrade) using various additives

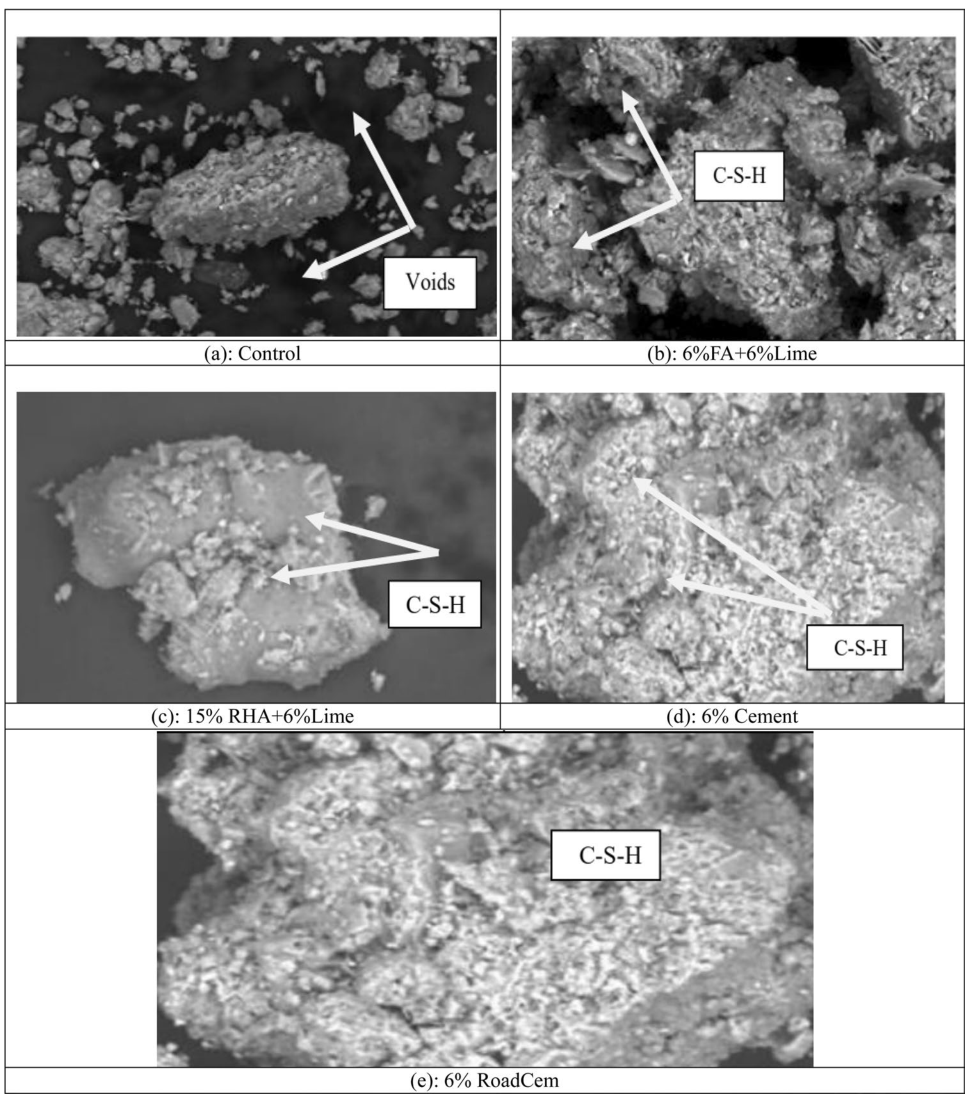

Fig. 13 Images of control and different stabilized admixtures under SEM

proves the previous outcomes from the engineering tests as CBR, UCS, and Mr. These findings are agreed with previous studies [62, 63].

Conclusions

- The selected optimum additives of the used materials are 6% cement, 6% RoadCem, 6% lime + 15% RHA, and 6% lime + 6% FA.
- The plasticity was decreased by adding all optimum additives.
- Adding the optimum additives to the tested soil increased MDD and decreased the OMC.
- All additives enhanced the compressive strength dramatically, the highest strength was observed at 6% RoadCem after 28 days and the lowest value was at 6% lime + 15% RHA.
- Blended soil with the selected additives at optimum percentages reduced FS%, and plasticity, which enhanced the performance of the subgrade layer.
- Treated soil with (RHA, FA) activated with Lime, cement, and RoadCem increased CBR and Mr. the highest values were found at 6% RoadCem; while, the lowest values occurred at the combination of 6% lime + 15% RHA.
- The relationships between Mr and both CBR and UCS seem to be linear with a high correlation factor R^2.
- Treating the subgrade layer with the selected optimum additives decreased the required base thickness for the flexible pavement section subjected to light, medium, and heavy traffic.
- The economically treated subgrade pavement section was determined to stabilize the subgrade with 6% RoadCem in the case of light traffic, then 6% cement.
- The soil stabilization of the subgrade layer is more effective in the case of light traffic.
- Qualitative correlations between the improved strength and the SEM analysis could be explained by observing the changes in the microstructures of the treated subgrade. It was observed that the growth of the chemical reaction product produced the C–S–H component. The results introduced a denser and stiffer clay structure, which led to an increase in strength after curing time. The results of the compressive strength test agreed well with the results from the SEM analysis observations.

Recommendations

Based on the outcomes of this study, the following points should be taken into consideration for future studies:

- Using the outcomes of this study and performing field test section under actual traffic loads.
- Perform mechanistic-empirical analysis using current study results to investigate the effect of these additives on flexible pavement design.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, an informed consent statement is not applicable.

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