ROAD MATERIALS AND PAVEMENT DESIGN
2022, VOL. 23, NO. 9, 2057–2075
https://doi.org/10.1080/14680629.2021.1950816

Taylor & Francis
Taylor & Francis Group

Geotechnical properties of lime-geogrid improved clayey subgrade under various moisture conditions

Soheil Jahandari[a], Zhong Tao[a], Mohammad Saberian[b], Mahdi Shariati[c], Jie Li[b], Masoumeh Abolhasani[d], Mostafa Kazemi[e], Aida Rahmani[a] and Maria Rashidi[a]

[a]Center for Infrastructure Engineering, Western Sydney University, Penrith, Australia; [b]School of Engineering, RMIT University, Melbourne, Australia; [c]Institute of Research and Development, Duy Tan University, Da Nang, Viet Nam; [d]Department of Civil and Environmental Engineering, Alaodoleh Semnani Institute of Higher Education, Garmsar, Iran; [e]GeMMe Building Materials, Urban and Environmental Engineering, University of Liège, Liège, Belgium

ABSTRACT

This research evaluated the effect of different moisture conditions on the ductility, geotechnical and microstructural characteristics of the improved clayey subgrade with various lime contents and geogrid layers. The results of more than 120 tests showed that the combined application of lime and geogrid to the clayey subgrade significantly enhanced the ductility and geotechnical characteristics by increasing the moisture content up to an optimal value. It was observed that higher water pressure led to the separation of the geogrid layers from the improved subgrade; thus, the uniformity, consistency, and geotechnical properties were significantly reduced. Microstructural analysis showed that increasing the amounts of moisture more than the optimal values caused more voids which led to a substantial decrease in the geotechnical properties as well as the physical bonding between geogrid layers and lime-stabilised soil. Finally, a simple prediction model was developed to estimate the geotechnical characteristics of the improved clayey subgrade.

ARTICLE HISTORY
Received 16 March 2020
Accepted 28 June 2021

KEYWORDS
Clay; moisture content; lime; geogrid; geotechnical properties; subgrade

1. Introduction

Problematic soils such as peats and soft clayey soils have weak geotechnical and physical properties which have to be treated for pavement subgrade applications; thus, the stabilisation of such problematic deposits is regarded as an important matter in civil engineering, particularly for road pavement projects (Rahgozar & Saberian, 2015; Cheshomi et al., 2017; Azadegan et al., 2012). Since the weak soils have high compressibility and poor shear strength, they are likely to have undesired settlements, which lead to a high level of risk in the construction of civil engineering structures such as pavements (Sadeghian et al., 2020; Tang et al., 2007). Swell and shrinkage properties are the main concerns of clay soils as subgrade of pavements. Shrinking and swelling of clayey soils are generally caused by the moisture variations which result in serious destructions to the pavement structure (Soltani et al., 2018; Sun et al., 2015).

The treatment of clay soils, as subgrade of pavements, by using different additives such as cement, fly ash, lime, and other cementing agents through pozzolanic reactions has been the focus of many previous studies (Eyo et al., 2020; Little, 1995; Pooni et al., 2019; Portland Cement Association, 1956; Rao et al., 2001; Salimi & Ghorbani, 2020; Sherwood, 1993; Yong & Ouhadi, 2007). In general, all lime-treated fine-grained soils show a decrease in plasticity and swelling potential, and an enhancement

CONTACT Soheil Jahandari s.jahandari@westernsydney.edu.au; Mahdi Shariati mahdishariati@duytan.edu.vn

in workability. However, not all soils exhibit a significant level of improved strength, which is due to pozzolanic reactivity. The level of improvement in physical properties exhibited in soils depends on the lime type, lime percentage, soil type and curing conditions (i.e. time, temperature and moisture). However, almost all fine-grained soils, regardless of soil-lime pozzolanic reactivity, acquire some level of physical property consistency improvement through lime treatment as reflected by changes in Atterberg limits and changes in volumetric measurements due to moisture fluctuations. The change of long-term soil properties (e.g. improvement in strength and deformation behaviour of soils) is also due to pozzolanic reactions that might depend on the type and amount of clay minerals and duration of interaction (Little, 1995).

Hajjaji and Mleza (2014) concluded that increasing the curing period and percentage of lime led to an increase in bending strength of lime-improved clay soil, as well as a decrease in water absorption and density. Increasing the OH ions concentration enhances the pH value during the addition of lime to the soil which in turn leads to silica and alumina being dissolved in the particles of clay soil (Ouhadi & Yong, 2003). Karematikerman et al. (2016) reported that an increase in the lime content reduces the volumetric shrinkage and increases the shear strength and UCS of the lime-treated clay soil. Based on the results of Garzón et al. (2016), it was observed that an increase in the lime content led to increasing the liquid limit, optimum moisture content, CBR, and coefficient of permeability, and decreasing plasticity index and maximum dry density. Ali and Mohamed (2018) concluded that by the addition of higher lime contents to the expansive clay, strength properties and permeability of the soil increased. It was also observed that higher curing temperature resulted in increasing strength properties and permeability.

Nevertheless, methods like the inclusion of geogrids are sometimes preferred in certain civil engineering projects, such as pavement construction, over other more complicated and expensive stabilisation methods such as pile and dynamic compaction (Rai et al., 2012; Zhu et al., 2009). Geogrids are usually used in pavements for granular subbases to improve rut resistance. So, the use of geogrid in fine-grained soils is not a typical application. In clayey soils, lime is usually used to decrease the swelling potential and increase the strength of the soil. Nevertheless, the use of lime in clayey soil stabilisation results in a significant decrease in the ductility and fracture strain of the stabilised soil. The ductility of lime-stabilised clay soil, as subgrade of pavements, can significantly be remedied by the application of geogrid. The application and mechanism of geogrids in developing flexible pavements were well investigated in previous studies such as Al-Qadi et al. (2008).

Because the addition of lime increases alkaline features of the stabilised soils, the use of geogrid is usually effective for such environments. However, the durability of geogrid in the alkaline medium must be first validated according to the relevant standards such as ISO/TS 13434 (2008). Rajesh and Viswanadham (2009) added geogrid to the clay soil and carried out a series of centrifuge tests. The laboratory test results illustrated that geogrid-reinforced soil endured large distortions. Distortion level can be defined using the ratio of central settlement at any stage of deformation to the influence length l within which differential settlement is induced. The value of l is defined as the distance between the mid-span of the clay barrier and the position 20 mm away from the hinge axis where the deformation is very little (i.e. it is 200 mm from the mid-span in model dimensions). Furthermore, the authors reported that even inducing a distortion level, as high as 0.125, did not cause a disturbance in the integrity of the stabilised soil. The results also showed that the inclusion of geogrid in the clay could provide a significantly better-stabilised soil compared to the untreated soil. Therefore, the swell-shrinkage properties of clay soils can be reduced by the inclusion of geogrid that is very important for pavement structure.

The literature review shows that adding lime to weak soils improves geotechnical properties. Besides, the adoption of lime decreases the swelling behaviour of clay, which is very important for the subgrade of pavements; however, it leads to a significant decrease in the ductility and fracture strain of the clay. Hence, the first objective of this research is to investigate the possible improvement of the ductility of lime-stabilised clay soil, as the pavement subgrade layer, by the inclusion of geogrid layers. The second and main objective is to evaluate the impacts of various moisture conditions on the geotechnical properties of lime-geogrid-improved clayey soil cured for 90 days. In this research, four layers of geogrid were added to the kaolinitic clay stabilised with different percentages of lime (0%, 3%, 5%, and 8%) and exposed to various moisture conditions to assess the geotechnical properties of the soil for pavement subgrade applications. Moreover, Scanning Electron Microscope (SEM) test was carried out to examine the microstructure of the stabilised soil. Finally, a prediction model was proposed to estimate the geotechnical properties of the improved soil, considering the moisture content/lime content ratio after 90 days of curing.

2. Properties of the materials

To measure the basic geotechnical properties of the kaolinitic clay soil, obtained from a road construction site in Kerman, Iran, ASTM standard tests were carried out. Figure 1 shows the sieve analysis of the tested clay soil, and Table 1 indicates its geotechnical characteristics. Chemical analyses of clay and lime were conducted by X-Ray Fluorescence (XRF) analysis using Bruker S4-Explorer, and the results are shown in Table 2. As can be seen from Table 2, the clay soil is principally characterised by SiO_2, Al_2O_3, and CaO with percentages of 41.75%, 15.15%, and 13.20%, respectively. Moreover, the total amount of SiO_2, Al_2O_3, and Fe_2O_3 in the clay soil is 62.10%, which is below the required minimum of 70.00% described in ASTM C618 (2015). Accordingly, for pavement subgrade applications, it is important to enhance the unconfined compressive strength and decrease the swell-shrinkage characteristics of the clay soil by the adoption of chemical additives such as lime (Rahgozar & Saberian, 2016; Sirivitmaitrie et al., 2011). Hydrated lime (called Artiman Ahak Type A), with a purity of about 70% and in compliance with the requirements of ASTM C977 (2000), was purchased from Mahboob Ahak Company in Kerman, Iran. Table 2 indicates that the used hydrated lime in this research is mainly made of calcium oxide (CaO). Moreover, the type of geogrid and its mesh size may affect the performance of pavement subgrade. The CE 121 geogrid utilised in the present research (supplied by MeshIran Company, Iran) is a common type of geogrid widely used in road and construction projects in Iran. In order to properly represent the condition of real pavement projects in the laboratory scale, the type of geogrid was required to have the highest number of elliptical meshes in the cross-section of the sample. Using this type of geogrid, 41 elliptical meshes were provided by each layer of geogrid in each cross-section

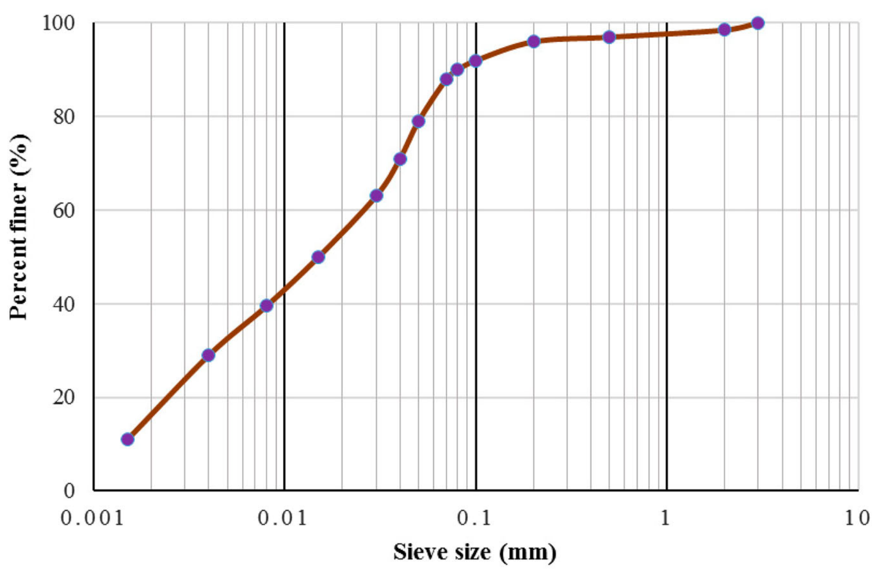

Figure 1. Sieve analysis of the soil (Jahandari et al., 2017).

Table 1. Characteristics of tested clayey soil.

Characteristics	Used standards	Results
Effective size (D_{10})	ASTM D422-63 (2002)	0.0015
Coefficient of curvature (C_C)	ASTM D422-63 (2002)	0.40
Coefficient of uniformity (C_u)	ASTM D422-63 (2002)	18
Type of soil	ASTM D2487 (2011)	CL
Activity degree	Das (1979)	0.47
Mineral	Das (1979)	Kaolinite
Plastic limit	ASTM D424-54 (1982)	23%
Liquid limit	ASTM D423-66 (1972)	33%
Plasticity index	ASTM D424-54 (1982)	10%
Specific gravity	ASTM D854 (2010)	2.46
Natural moisture content	ASTM D2216 (2010)	24.75%
Optimum moisture content	ASTM D1557 (2007)	15%
Maximum dry density	ASTM D1557 (2007)	18.74 kN/m^3
Swelling index (C_S)	ASTM D2435M (2011)	0.05
Compression index (C_C)	ASTM D2435M (2011)	0.21
Reloading index (C_r)	ASTM D2435M (2011)	0.39

Table 2. Chemical characteristics of the lime and clay.

Component oxides	Lime (%)	Clay (%)
SiO_2	–	41.75
CaO	68.46	13.20
Al_2O_3	1.45	15.15
MgO	3.10	5.13
Fe_2O_3	0.70	5.20
SO_3	–	3.48
LOI	23.07	12.58
CL	–	0.08

Table 3. Basic properties of the CE 121 geogrid (Jahandari et al., 2017c).

Size of elliptical mesh	Type of polymer	Tensile strength per unit of length	Dimension	Weight per unit of area
6 × 8 mm	HDPE	69.5 kN/m	2.5 × 30 m	730 gr/m^2

of the sample, which could greatly eliminate the effect of scale and represent the real conditions in lime-geogrid improved clayey subgrade projects. It should be noted that further research is required to study the influence of geogrid properties on the behaviour of soil. Table 3 presents the characteristics of the used geogrid. The high-density polyethylene (HDPE) polymer used in this geogrid is known for its resistance to corrosion so that the existence of alkaline and acidic substances in the soil does not affect the performance of the geogrid. The quality of water also has a significant influence on the mechanical characteristics of stabilised soils and cementitious materials (Gholhaki et al., 2017). Therefore, tap water was utilised for molding the samples, and distilled water was used for the characterisation tests (Afshar et al., 2020; Jahandari et al., 2017b; Jahandari et al., 2019).

3. Sample preparation and testing programme

The clay soil used in this study had an initial moisture content of 24.80%, as shown in Table 1. Before carrying out the compaction test and preparing the samples for uniaxial compression tests, the soil was dried in an oven at 100°C until a constant mass was achieved. To measure the maximum dry density ($\gamma_{d,\max}$) and optimum moisture content (ω_{opt}) and assess the impacts of moisture contents on the geotechnical characteristics of the lime-improved and lime-geogrid-improved clay as subgrade of pavements, standard Proctor compaction test was carried out according to ASTM D1557 (2007).

Figure 2 shows the compaction test results. Obviously, by increasing the lime content, ω_{opt} increased and $\gamma_{d,\max}$ decreased. The results are similar to the findings of Garzón et al. (2016) on the effects of lime on phyllite clay. There are two reasons for the reduction in maximum dry density and the increase in optimum water content as a result of adding lime to the soil. Firstly, the specific gravity of lime is lower than that of the clayey soil. Secondly, lime increases the optimum water content for compaction, which is advantageous while dealing with wet soils. Flocculation and cementation make the soil more difficult to compact; as a result, the maximum dry density achieved with a specific compaction effort is reduced. To prepare the specimens, dried clay soil was first well blended with different percentages of lime (i.e. 0%, 3%, 5%, and 8% of the dry weight of the clay soil) through the use of an automatic stainless steel mixer (Hobart N50-619 Liter 5 Quart Planetary Mixer) for about four minutes until a homogeneous blend was achieved. Then, the soil-lime mixture was further mixed well at the relevant optimum moisture content (MC) as well as various modified water contents (i.e. optimum MC $\pm$ 2% or $\pm$ 4% water contents) to evaluate the effects of different moisture contents on the geotechnical properties of lime-geogrid-improved clay soil as subgrade of pavements. Basically, the percentages of water added to the specimen mixed with 3% lime having the optimum water content of 19.80%, were set at 17.80%, 15.80%, 21.80%, and 23.80%. Besides, the percentages of water added to the specimen containing 5% lime having the optimum water content of 23.56%, were considered at 21.56%, 19.56%, 25.56%, and 27.56%. At last, the percentages of water added to the specimen mixed with 8% lime having the optimum water content of 24.00%, were considered at 22.00%, 20.00%, 26.00%, and 28.00%. In the reinforced samples, because the lime-stabilised specimens were compacted in five layers, geogrid was placed in 4 layers at the boundaries of the compacted layers at constant intervals. It is also important to note that all the specimens in this study were prepared with 100% compaction energy. Three replicate specimens were prepared for each blend and the mean values were measured and reported. After unmolding, the samples were placed in plastic bags to prevent moisture variations during the curing period. After a 90-day curing period at the ambient temperature of 25°C and relative humidity of 95%, uniaxial compression strength tests were carried out on the samples based on ASTM D5102 (2009). More details of the UCS tests and sample preparations can be found in the research studies of Jahandari et al. (2017a, 2019). Subgrade and subbase are mostly designed based

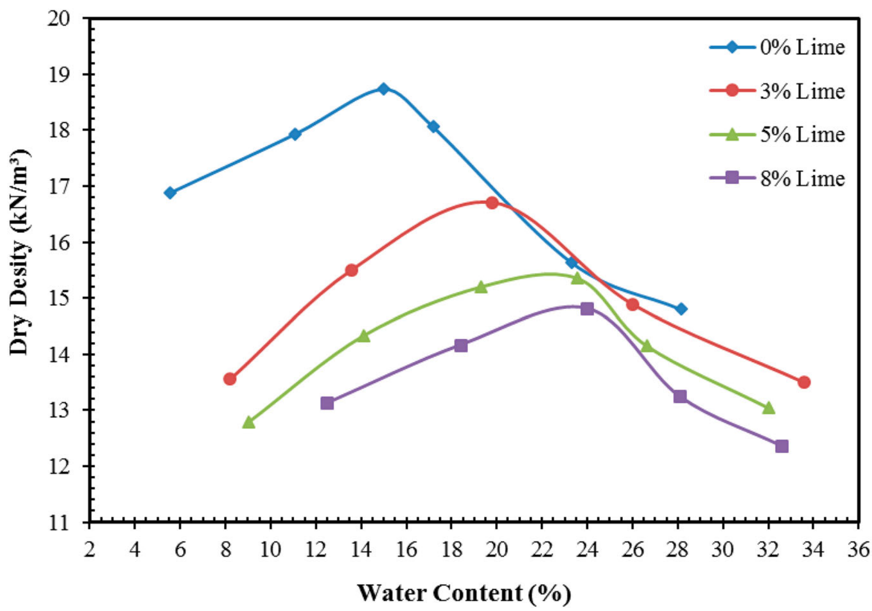

Figure 2. Results of standard Proctor compaction test (Jahandari et al., 2017).

on CBR. However, there were a few reasons for which the authors considered the UCS test in this study. First, the predominant type of fine-grained soil in Kerman city is a unique type of clayey soil which has swelling potential in some parts of the city and high collapsibility index in some other parts. Such soils are observed in some other parts of the world as well (Avila & Pantoja, 2018). After the construction of subgrade on these types of soils, it has been observed for many times that the crack propagation in chemically-treated subgrade results in the destruction of subbase, base, and ultimately pavement. In order to alleviate such destructions, geogrids can act as bridging ligaments behind crack tips to resist crack and improve the integrity of the road materials. However, such behaviour resulted from the application of geogrids in lime-stabilised clayey subgrade can be observed from the stress–strain behaviour through UCS test results. Moreover, because the geogrids greatly improve the integrity of the road materials, it can be expected that the CBR of lime-stabilised soil will also increase by the application of geogrid layers. VEGA3 TESCAN apparatus was also utilised to investigate the impacts of lime and moisture content on the microstructure of the clay soil.

4. Results and discussion

4.1. Stress–strain behaviour and secant modulus (E_S)

Unconfined Compressive Strength (UCS) test was carried out to assess the impacts of moisture content (MC) on UCS, stress–strain behaviour, and E_S of the clayey soil stabilised with lime, reinforced with geogrid layers, and used as subgrade of pavement.

The test was conducted on cured lime-improved specimens with lime contents of 0%, 3%, 5%, and 8%, as well as on lime-geogrid-improved specimens, both after the 90-day curing period. Figure 3 illustrates the effects of different moisture contents on the stress–strain behaviour of the stabilised specimens mixed with 8% lime after 90 days of curing. Likewise, Figure 4 shows the effects of different moisture contents on stress–strain behaviour of specimens stabilised with 8% lime and reinforced with geogrid layers after 90-day curing period. Similar trends were also observed for the samples stabilised with 3 and 5% lime. Moreover, the graphs in Figures 3 and 4 provide the maximum UCSs of the specimens. In addition, E_S was measured by dividing 50% of the maximum compressive strength by the uniaxial strain corresponding to 50% of the maximum compressive strength (Rahgozar & Saberian, 2016). E_S and maximum UCS of specimens having different moisture contents and 0%, 3%, 5%, and 8% lime contents with/without geogrids are also reported in Tables 4–6. According to the results, it can be observed that lime, geogrid, and moisture had significant effects on the geotechnical properties of the clay soil that will be analysed as follows.

The UCS test results show that UCS and E_S of the untreated clay were at 407.00 kPa and 14.03 MPa, respectively. However, the improved clay with 8% lime and geogrid layers after 90-day curing period at the optimum moisture content of 24% achieved the highest values of UCS and E_S at 1589.10 kPa and 198.63 MPa, respectively. Similar values of UCS for lime treated clay were also reported by Mirzababaei et al. (2013).

An increase in the lime content led to a remarkable increase in the geotechnical properties of the specimens. According to the results, by increasing the lime content from 0% to 8%, the UCS and E_S of the samples having the optimum moisture contents increased from 726.45 to 1258.74 kPa and from 71.51 to 170.10 MPa, respectively, which means that an increase of 73.27% and 57.96%, respectively. Chemeda et al. (2015), Jha and Sivapullaiah (2015), and Khemissa and Mahamedi (2014) also observed similar results from the stabilisation of clay soils with lime. Also, UCS and E_S increased from 1360.03 to 1589.10 kPa and from 103.03 to 198.63 MPa, respectively, which rose by 16.84% and 92.78%, respectively as the percentage of lime increased from 3% to 8% for the lime-geogrid-improved samples at their optimum moisture contents.

Applying the geogrid layers played a substantial role in improving the geotechnical properties of the stabilised clay. For instance, for the geogrid-stabilised specimen with 8% lime at its optimum moisture content, the values of UCS and E_S were 3.11 and 3.92 times higher than those of the values for

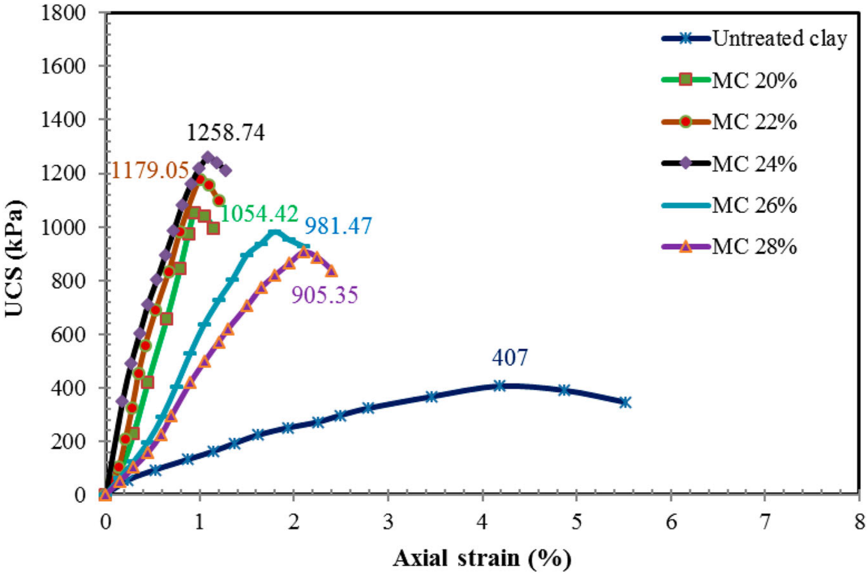

Figure 3. Stress-strain behaviour of specimens improved with 8% lime having different moisture contents.

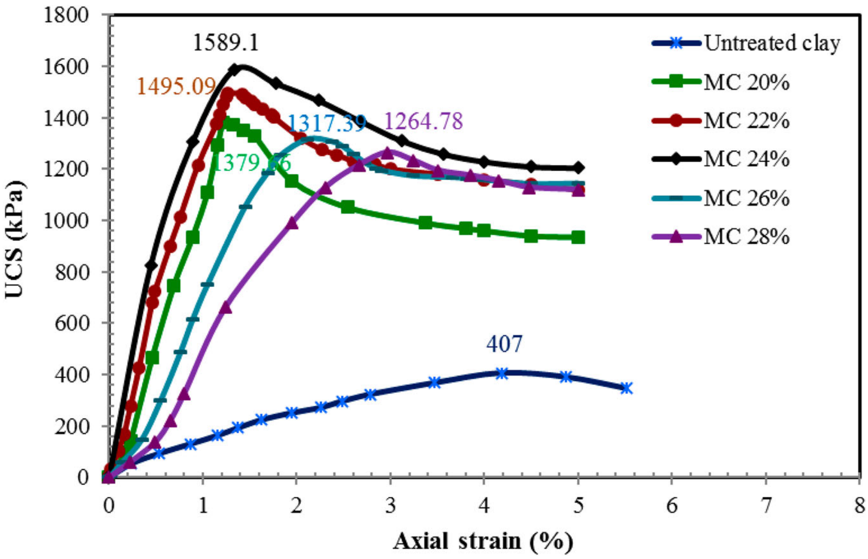

Figure 4. Stress-strain behaviour of specimens improved with 8% lime and geogrid having different moisture contents.

the untreated clay, respectively. In addition, at a given amount of lime, by addition of geogrid layers, geotechnical properties of the lime-geogrid-improved specimens improved at higher rates compared to those of the lime-improved specimens. As an example, by addition of 5% lime, UCS and E_s of the lime-geogrid-stabilised specimen at its optimum MC were 1.25 and 1.10 times higher than those of the values for the lime-stabilised specimen, respectively.

From Figures 3 and 4 and Tables 4–6, it is evident that moisture content is a key parameter and has substantial effects on the geotechnical properties of the clay soil. First of all, by increasing the MC up to the optimum MC, the geotechnical properties such as UCS and E_s increased. But, when the MC

Table 4. Geotechnical properties of the specimens with 3% lime and different moisture contents.

Property \ Specimens	Untreated soil	Stabilised soil with 3% lime					Stabilised soil with 3% lime and geogrid				
		Moisture content (%)					Moisture content (%)				
		15.80	17.80	19.80	21.80	23.80	15.80	17.80	19.80	21.80	23.80
ε_f (%)	4.18	1.13	1.16	1.28	1.82	1.89	1.55	1.59	1.76	3.61	4.01
I_D	–	0.27	0.28	0.30	0.43	0.45	0.37	0.38	0.42	0.86	0.96
E_s (MPa)	14.03	50.90	59.70	71.51	38.40	31.16	59.31	90.38	103.03	29.40	17.60
M_r (MPa)	119.27	142.02	156.20	158.88	149.76	144.53	204.13	223.46	237.44	176.74	164.61
G (MPa)	4.68	16.97	19.90	23.84	12.80	10.39	19.77	30.13	34.34	9.80	5.87
K (MPa)	7.79	28.28	33.17	39.73	21.33	17.31	32.95	50.21	57.24	16.33	9.78

Table 5. Geotechnical properties of the specimens with 5% lime and different moisture contents.

Property \ Specimens	Untreated soil	Stabilised soil with 5% lime					Stabilised soil with 5% lime and geogrid				
		Moisture content (%)					Moisture content (%)				
		19.56	21.56	23.56	25.56	27.56	19.56	21.56	23.56	25.56	27.56
ε_f (%)	4.18	1.04	1.12	1.18	1.88	1.83	1.35	1.40	1.50	2.24	4.00
I_D	–	0.25	0.27	0.28	0.44	0.43	0.32	0.34	0.35	0.54	0.95
E_s (MPa)	14.03	84.00	101.76	123.77	55.53	48.97	87.03	110.23	136.23	54.97	39.96
M_r (MPa)	119.27	187.55	202.56	217.05	183.12	179.32	223.30	243.76	254.61	218.77	209.53
G (MPa)	4.68	28.00	33.92	41.26	18.51	16.32	29.01	36.74	45.41	18.23	13.32
K (MPa)	7.79	46.67	56.53	68.78	30.85	27.21	48.35	61.24	75.68	30.54	22.20

Table 6. Geotechnical properties of the specimens with 8% lime and different moisture contents.

Property \ Specimens	Untreated soil	Stabilised soil with 8% lime					Stabilised soil with 8% lime and geogrid				
		Moisture content (%)					Moisture content (%)				
		20.00	22.00	24.00	26.00	28.00	20.00	22.00	24.00	26.00	28.00
ε_f (%)	4.18	0.95	1.00	1.09	1.80	2.10	1.22	1.27	1.34	2.12	2.97
I_D	–	0.23	0.24	0.26	0.43	0.50	0.29	0.30	0.32	0.50	0.71
E_s (MPa)	14.03	99.47	137.09	170.10	57.73	49.20	106.13	149.51	198.63	70.45	54.99
M_r (MPa)	119.27	199.55	215.00	224.88	190.50	181.06	239.88	254.19	265.85	232.16	225.63
G (MPa)	4.68	33.16	45.69	56.70	19.24	16.40	35.38	49.84	66.21	23.48	18.33
K (MPa)	7.79	55.26	76.17	94.50	32.07	27.33	58.96	83.06	110.35	39.14	30.55

was increased further, the geotechnical properties decreased. This could be attributed to the swell-expansion behaviour of clay and water pressure in the specimens. For example, for the lime-stabilised specimens with 3% of lime, by increasing the MC from 15.80% to 19.80%, UCS and E_s increased from 590.49 to 726.45 kPa and from 50.90 to 71.51 MPa, respectively, and by increasing the MC from 19.80% to 23.80%, UCS and E_s decreased from 726.45 to 610.69 kPa and from 71.51 to 31.16 MPa, respectively. Besides, at lower lime contents, the effect of increasing MC was more significant than its effect at higher lime contents. The results showed that UCS increased by 25% by increasing MC up to the optimum moisture content (i.e. from 15.80% to 19.80%) for the geogrid-lime-improved samples with 3% lime. However, UCS increased by 16% by increasing MC to the optimum moisture content (i.e. from 20.00% to 24.00%) for the geogrid-lime-improved samples with 8% lime.

Another finding is that by adding water higher than the optimum MC, effects of water on the geotechnical characteristics of the lime-geogrid-improved samples were more than its effects on the properties of those of the lime-improved samples. For example, by increasing the MC from 23.56% to 27.56%, E_s of the stabilised specimen with 5% lime decreased from 123.77 to 48.97 MPa, which decreased by 60.43%. However, by increasing the MC from 23.56% to 27.56%, E_s of the lime-geogrid-improved specimen with 5% lime decreased from 136.23 to 39.96 MPa, which reduced by 70.66%.

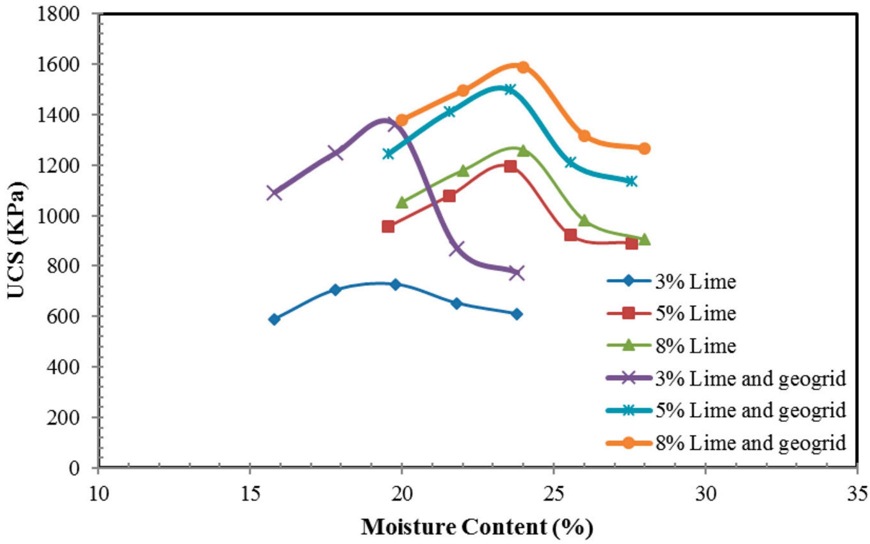

Figure 5. Variations of UCS vs moisture content in specimens improved with 3%, 5% and 8% lime and 3%, 5% and 8% lime reinforced with geogrid.

These effects are due to the fact that by increasing the MC more than the optimum MC in the lime-geogrid-improved specimens, higher water pressure leads to the separation of geogrid layers from the lime-stabilised soils and therefore homogeneity and consistency of the specimens were reduced. Figure 5 shows the effects of various moisture contents on the UCS of the specimens reinforced with and without geogrid layers.

4.2. Resilient modulus (M_r), shear modulus (G), bulk modulus (K), failure strain (ε_f), and deformability index (I_D)

Resilient modulus (M_r) describes the response of pavement layers to traffic loadings, and it is an important design parameter for flexible pavements (AASHTO T307, 2005; Saberian et al., 2019). Several factors such as compaction, index properties, loading condition, natural water content, coarse-grained or fine-grained materials, and gradation of soil affect this property (Han & Vanapalli, 2016; Miao et al., 2016; Saberian et al., 2020; Sadrossadat et al., 2016). M_r can be calculated from Equation (1) (Thompson, 1966).

$$M_r(MPa) = 0.124 \times \text{UCS}(kPa) + 68.8 \quad (1)$$

On the other hand, shear modulus G is used for site response analysis and pavement structural designs. Soil with a low G may cause distortion of pavement and even loss of lives (Carlton & Pestana, 2016). Shear modulus can be obtained from Equation (2) (Selvadurai & Katebi, 2013).

$$G(MPa) = \sigma_{xy}/(\varepsilon_{xy} + \varepsilon_{yx}) = \sigma_{xy}/2\varepsilon_{xy} = \sigma_{xy}/\gamma_{xy} = E_s(MPa)/2(1 + \upsilon) = E_s(kPa)/3 \quad (2)$$

where, σ_{xy}, ε, υ and E_s are shear stress, shear strain, Poisson's ratio, and secant modulus, respectively. Also, based on the research conducted by Selvadurai and Katebi (2013), $\gamma_{xy} = \varepsilon_{xy} + \varepsilon_{yx} = 2\varepsilon_{xy}$. According to some previous studies, the Poisson's ratio is assumed to be 0.50, which is a logical ratio for the lime-stabilised soil used in this research (Jahandari et al., 2017c; Péterfalvi et al., 2015). Poisson's ratio of lime-treated soil is a stress dependent property. Based on the recent study conducted by Péterfalvi et al. (2015), the Poisson ratio can vary between $0 \leq \mu \leq 0.5$ for lime-stabilised soils. When the soil is considered as stabilised cohesive soil (clay), the value of $\mu = 0.5$ could be considered.

Besides, bulk modulus (K) is used to evaluate the elastic properties, plastic shrinkage cracking, early aged shrinkage, and plastic settlement of soils (Ghourchian et al., 2016). Therefore, the bulk modulus is regarded as an important parameter for flexible pavements. This parameter is obtained by dividing the change in overall stress by the change in volumetric strain using Equation (3) (Duncan & Bursey, 2013; Hobbs, 1971):

$$K = \sigma/(\Delta V/V) = \sigma/(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) = E_s/3(1 - 2\upsilon) \tag{3}$$

Where, σ, $\Delta V/V$, ε_{xx}, ε_{zz}, ε_{yy}, E_s, and υ are hydrostatic pressure, relative volume change, direct strains, secant modulus, and Poisson's ratio, respectively (Hobbs, 1971). M_r, G, and K of the specimens with 3, 5, and 8% lime and different moisture contents are provided in Tables 4–6.

Based on the test results, it can be observed that M_r, G, and K of the untreated clay made up at 119.27, 4.68, and 7.79 MPa, respectively. However, the geogrid-reinforced clay stabilised with 8% lime after the 90 d-curing period at the optimum moisture content of 24% achieved the highest values of M_r, G, and K at 265.85 MPa, 66.21 MPa, and 110.35 MPa, respectively.

For the geogrid-improved specimen with 8% lime at its optimum moisture content, the values of M_r, G, and K were 1.89, 3.92, and 3.92 times higher than those of the values of the untreated clay, respectively. In addition, at constant amounts of lime, by addition of geogrids, properties of the improved specimens were improved more than those of the lime-stabilised specimens. As an example, by addition of 5% lime, M_r, G, and K of the lime-geogrid-improved specimen at the optimum MC were 1.17, 1.10, and 1.10 times higher than those of the values of the lime-stabilised specimen, respectively.

ε_f is the strain corresponding to the maximum UCS. Another parameter that can be used to examine the deformation properties of pavement layers is deformability index (I_D), which is determined from Equation (4) (Li et al., 2018; Park, 2011; Saberian et al., 2019).

$$I_D = \varepsilon_{ct}/\varepsilon_{cu} \tag{4}$$

Where ε_{cu} is the axial strain corresponding to the uniaxial compressive strength of untreated clay soil and ε_{ct} is the axial strain corresponding to the uniaxial compressive strength of stabilised samples. Deformability index and failure strain of the specimens are presented in Tables 4–6.

For ductile materials, up to the failure line, most of the generated energy is plastic. However, the strain–stress curve for brittle materials proceeds by a steep linear line and an elastic deformation before a sudden fracture (Saberian & Rahgozar, 2016). According to Figures 3 and 4 and Tables 4–6, it can be concluded that increasing the lime percentages caused the failure and fracture strains to decrease.

In addition, the ductile and/or brittle behaviours of materials can be interpreted by using I_D. It can be seen from the UCS results that the deformability index of specimens decreased by increasing the lime percentage. Consequently, an increase in the lime content from 3 to 8% resulted in a decrease in deformability index from 0.30 to 0.26 for the lime-treated specimens at their optimum moisture contents. Basically, an increase in lime content in the lime-treated clay soil not only caused the swelling potential of the specimen to decrease, but also resulted in an increase in the bearing capacity.

Adoption of geogrids into the soil not only improved the geotechnical properties, but also played a substantial role in plastic and ductile behaviours of the samples. First of all, at constant amounts of lime, adding geogrids resulted in a significant increase in the failure and fracture strains. In addition, the lime-geogrid-stabilised specimens exhibited semi-ductile behaviour compared to the strain–stress curves of lime-stabilised and unimproved specimens that demonstrated brittle and ductile behaviours, respectively. The reason is that initially there are steep linear elastic curves as well as energy absorptions and plastic deformations before a fracture. Moreover, the deformability index of specimens increased by adding geogrid layers. For instance, at a constant amount of lime of 3% at its optimum moisture content of 19.80%, deformability index of the lime-geogrid-improved specimen was 1.40 times higher than that of the deformability index of the lime-stabilised specimen. Therefore, the lime-geogrid-improved specimens indicated more ductile behaviour than those of the lime-stabilised specimens. Such behaviours were also observed by Azadegan et al. (2013) on the effect of the application of geogrid, lime, and cement to the granular soils.

Water addition had a significant impact on the ductility of specimens. Initially, the deformability index and failure strain of specimens rose with an increase in the MC. Moreover, from Figures 3 and 4 and Tables 4–6, it can be inferred that by increasing the MC, lime-geogrid-improved specimens demonstrated more ductile behaviour than those of the lime-stabilised specimens. As MC increased from 20% to 28%, deformability index of the stabilised soil with 8% lime increased from 0.23 to 0.50; however, deformability index of geogrid-stabilised soil with 8% lime increased from 0.29 to 0.71. In addition, increasing MC higher than the optimum MC led to more obvious ductile behaviour than increasing the MC up to the optimum MC. For instance, the deformability index increased from 0.27 to 0.30 by an increase in the MC from 15.80% to 19.80% for the stabilised specimen with 3% lime. However, the deformability index increased from 0.30 to 0.45 by an increase in the MC from 19.80% to 23.8%.

4.3. Scanning Electron micrograph (SEM)

Figure 6 illustrates the results of SEM for air-dried clay soil as well as the treated clay soil sample with 8% lime and 28% moisture after 90 days of curing.

According to Figure 6, voids in random orders can be identified in the untreated clay. A well-structured matrix can be observed for the lime treated clay although the impact and penetration of water are obviously noticeable in the middle part of the specimen. Increasing the MC led to the lime being dissolved and decayed, and created crystals with weak bonds between the lime and soil particles. More importantly, it can be seen that higher moisture contents also caused the formation of large voids which led to a significant decrease in the geotechnical properties and separation of geogrid layers from the lime-stabilised soil.

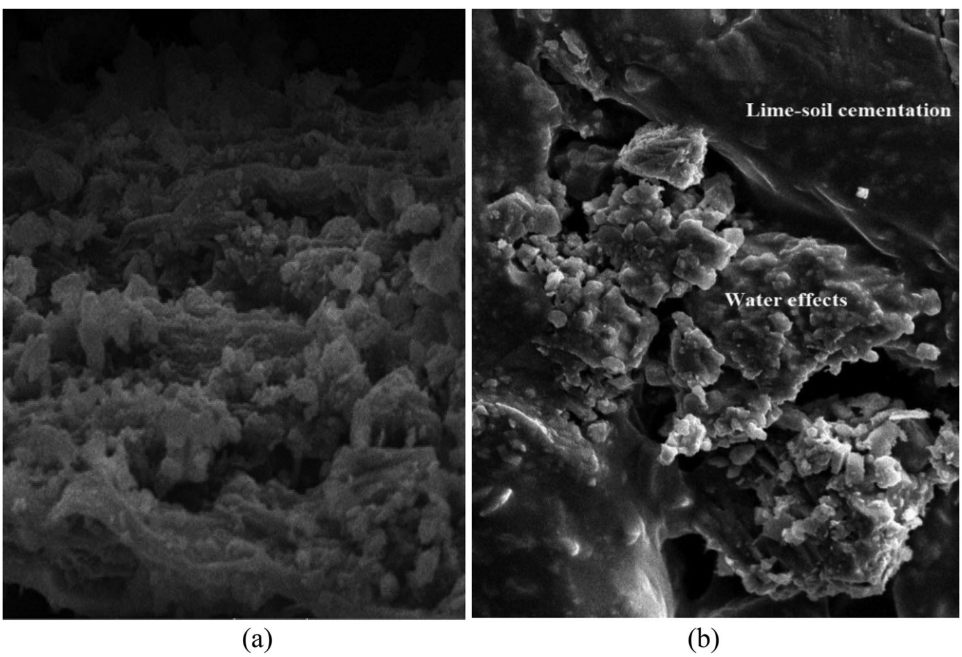

Figure 6. The results of SEM for (a) the untreated clay (Jahandari et al., 2017a) and (b) the treated clay with 8% lime containing 28% moisture after 90 days of curing (SEM HV: 20 kV, WD: 14.59 mm, View field: 63.8 μm, SEM MAG: 2.98 kx).

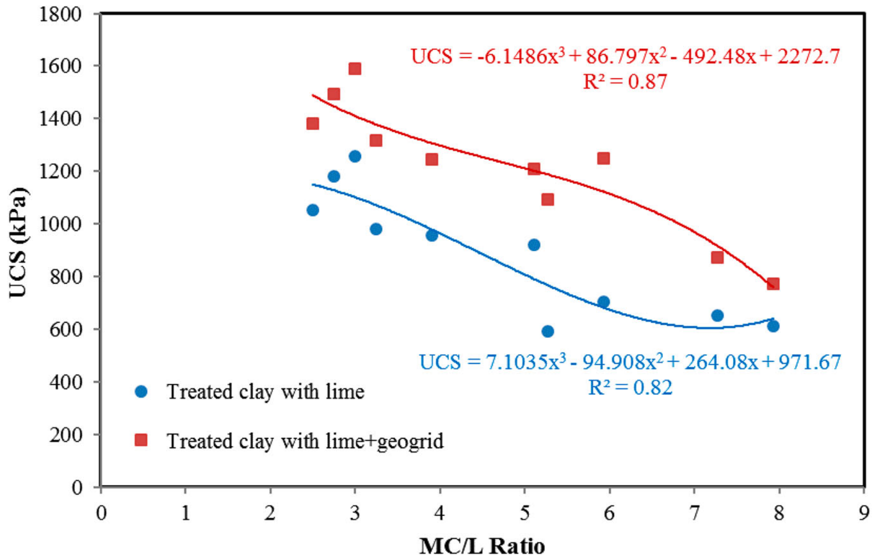

Figure 7. The curve fitted to UCS development through the MC/L ratio hypothesis.

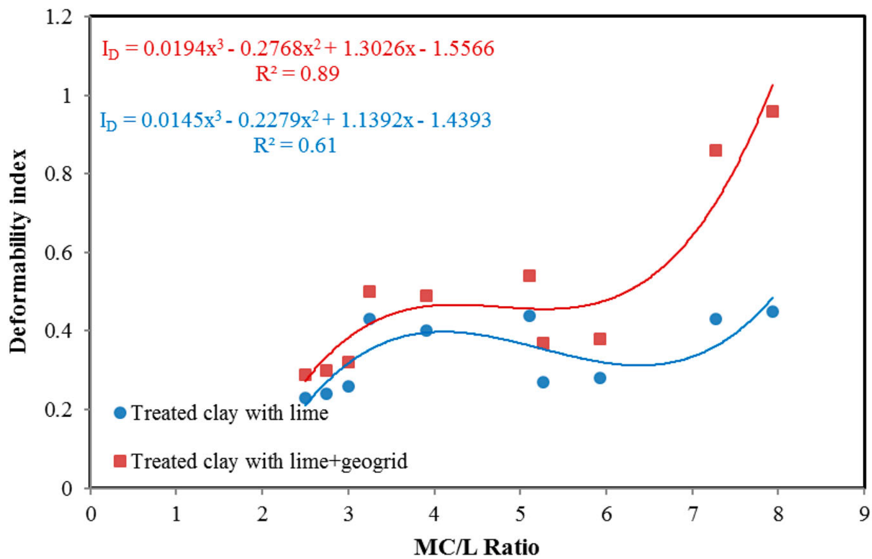

Figure 8. The curve fitted to I_D development through the MC/L ratio hypothesis.

5. Prediction model

The results reported in the last section demonstrate that lime contents, geogrid layers, and moisture content significantly affected the geotechnical properties. But, the percentages of lime and/or moisture contents in a real-life subgrade stabilisation project may not be the same as the tested amounts in this study. In addition, experimental tests for studying the effects of various ranges of moisture and lime contents could be time-consuming and expensive. Thus, prediction of the properties using a simple prediction model is one of the most feasible ways to assess the impacts of different percentages of lime and water on the geotechnical properties. In this regard, Saberian et al. (2017, 2017), Consoli et al. (2010), and Cong et al. (2014) utilised the power function to predict the UCS according to the

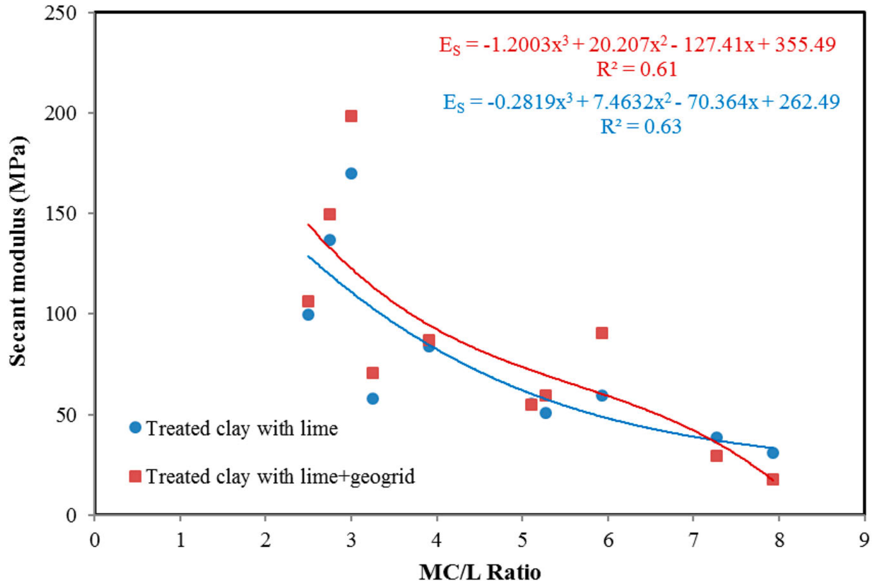

Figure 9. The curve fitted to E_s development through the MC/L ratio hypothesis.

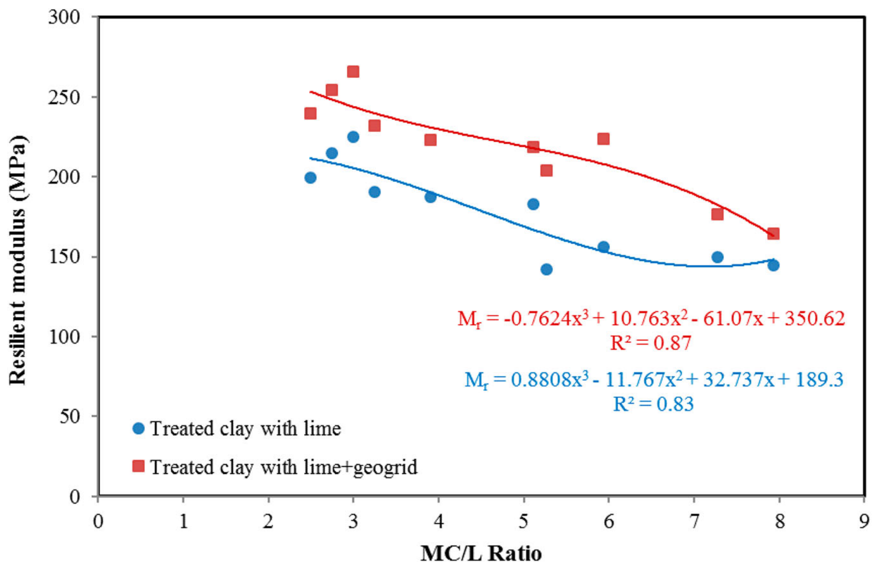

Figure 10. The curve fitted to M_r development through the MC/L ratio hypothesis.

cementitious content (Equation (5)) since the power function is the most widely used model to fit the laboratory test results between UCS and the binder content (C). Therefore, similar equations can be developed for the prediction of E_s, UCS, I_D, G, M_r, and K of lime-improved clay and geogrid-lime-improved clay by considering the MC/L (moisture content/lime content) ratio as the main variable. Equation (6) illustrates the relationship between MC/L ratio and each property.

$$\text{UCS} = a \times (C)^b \tag{5}$$

$$Y = a \times (MC/L)^b \tag{6}$$

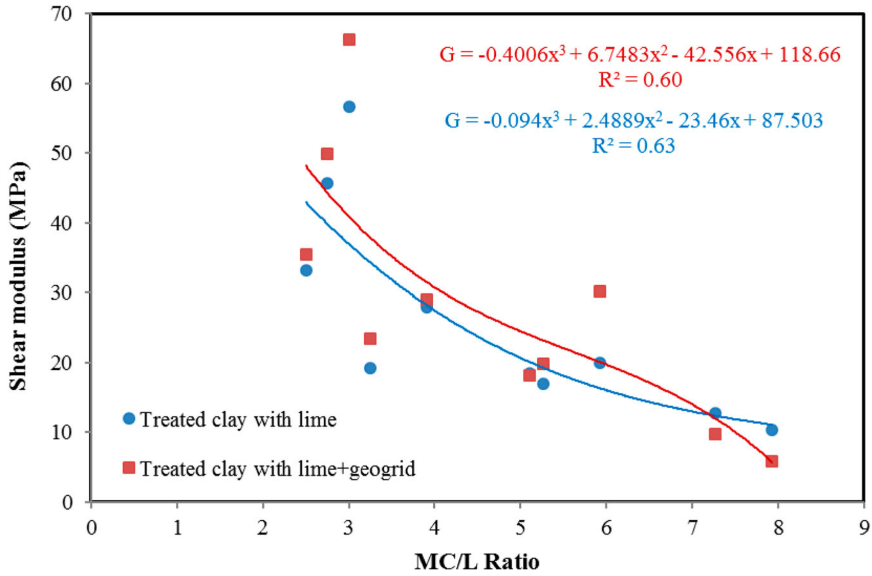

Figure 11. The curve fitted to G development through the MC/L ratio hypothesis.

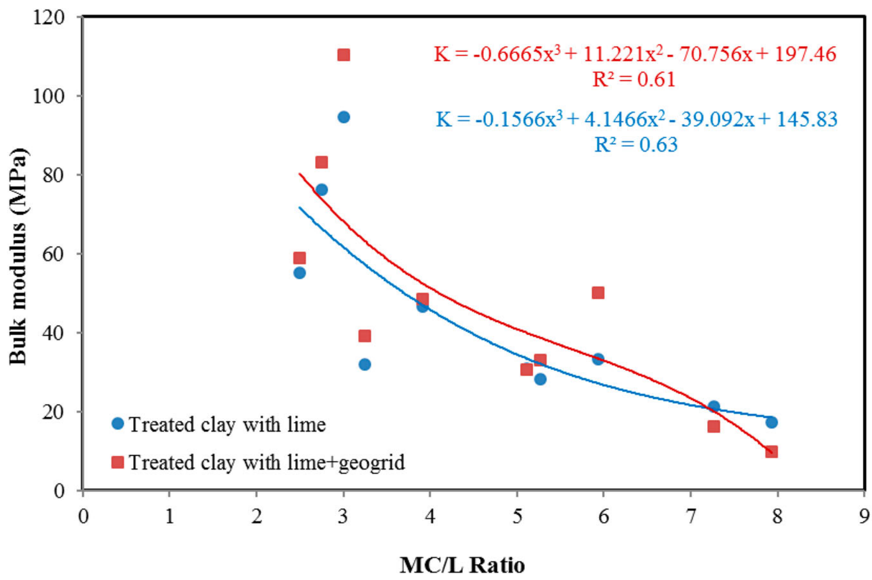

Figure 12. The curve fitted to K development through the MC/L ratio hypothesis.

Where the fitting parameters are a (in kPa, MPa, or dimensionless depends on the parameter) and b (dimensionless parameter). In addition, MC, *C*, and *L* are moisture content, cement percentage, and lime percentage, respectively. Figures 7–12 represent the fitted curves for the UCS-(MC/*L*), I_D-(MC/*L*), E_s-(MC/*L*), M_r-(MC/*L*), *G*-(MC/*L*), and *K*-(MC/*L*) relationships, respectively.

Twelve equations were obtained and provided in Figures 7–12 based on the MC/*L* ratio to reasonably predict the UCS, I_D, E_s, M_r, *G*, and *K* of the Kaolinitic clay reinforced with geogrid layers and improved with lime, which was cured for 90 days for subgrade application. Table 7 shows the equations of the properties obtained from the prediction model. The coefficient of determination of each parameter through the experimental and prediction model calculation is also provided in Table 7.

Table 7. Equations of the prediction model of the stabilised clay specimens according to the relationships between UCS-*L*, E_s-*L*, I_D-*L*, M_r-*L*, *G*-*L*, and *K*-*L* after 90 curing days.

Model	Treated clay with lime	Treated clay with lime and geogrid
UCS-*L*	$\text{UCS} = 7.1035\times^3 - 94.908\times^2 + 264.08\times + 971.67$ $R^2 = 0.82$	$\text{UCS} = -6.1486\times^3 + 86.797\times^2 - 492.48\times + 2272.7$ $R^2 = 0.87$
E_s-*L*	$E_S = -0.2819\times^3 + 7.4632\times^2 - 70.364\times + 262.49$ $R^2 = 0.63$	$E_S = -1.2003\times^3 + 20.207\times^2 - 127.41\times + 355.49$ $R^2 = 0.61$
I_D-*L*	$I_D = 0.0145\times^3 - 0.2279\times^2 + 1.1392\times - 1.4393$ $R^2 = 0.61$	$I_D = 0.0194\times^3 - 0.2768\times^2 + 1.3026\times - 1.5566$ $R^2 = 0.89$
M_r-*L*	$M_r = 0.8808\times^3 - 11.767\times^2 + 32.737\times + 189.3$ $R^2 = 0.82$	$M_r = -0.7624\times^3 + 10.763\times^2 - 61.07\times + 350.62$ $R^2 = 0.87$
G-*L*	$G = -0.094\times^3 + 2.4889\times^2 - 23.46\times + 87.503$ $R^2 = 0.63$	$G = -0.4006\times^3 + 6.7483\times^2 - 42.556\times + 118.66$ $R^2 = 0.60$
K-*L*	$K = -0.1566\times^3 + 4.1466\times^2 - 39.092\times + 145.83$ $R^2 = 0.63$	$K = -0.6665\times^3 + 11.221\times^2 - 70.756\times + 197.46$ $R^2 = 0.61$

Conclusions

The objective of this research was to investigate the geotechnical properties of lime-geogrid improved clayey soil under various moisture conditions for pavement subgrade application. Initially, compaction tests were conducted on the stabilised samples with 0%, 3%, 5%, and 8% lime to determine the optimum moisture contents (MC) and maximum dry densities. Then, different water percentages were applied to the lime-soil mixture, and UCS tests were carried out on the samples after 90-day curing period to examine the impacts of MC on the geotechnical characteristics of both lime-improved clay and lime-geogrid-improved clay. Finally, some useful equations to predict UCS, E_s, I_D, M_r, *G*, and *K* based on the ratio of moisture content/lime content were obtained using a simple prediction model. The following main conclusions could be drawn from the results:

(1) The measured UCS, E_s, M_r, *G*, and *K* of the untreated clay were 407.00 kPa, 14.03 MPa, 119.27MPa, 4.68 MPa, and 7.79 MPa, respectively. However, the geogrid-reinforced clay improved with 8% lime after 90-day curing period at the optimum moisture content of 24% achieved the highest values of UCS, E_s, M_r, *G*, and *K* at 1589.10 kPa, 198.63 MPa, 265.85 MPa, 66.21 MPa, and 110.35 MPa, respectively.
(2) By increasing the lime percentage and applying four layers of geogrid to the specimens, the geotechnical properties of specimens increased significantly.
(3) At constant amounts of lime, by addition of geogrids, properties of the lime-geogrid-improved specimens improved more than those of the lime-stabilised specimens.
(4) By increasing the MC up to the optimum MC, the geotechnical properties increased and then by increasing the MC further, the properties decreased. Moreover, at lower lime contents, the effect of increasing MC was more than its effect at higher percentages of lime.
(5) Surprisingly, by adding water content higher than the optimum MC, effects of water on geotechnical characteristics of the lime-geogrid-improved samples were more than its effects on the properties of those of the lime-stabilised specimens. This effect was due to the fact that by increasing the MC more than the optimum MC in the lime-geogrid-improved specimens, higher water pressure led to the separation of the geogrid layers from the lime-stabilised soils, which resulted in the homogeneity and consistency of specimens to fade away.
(6) By increasing the lime content, deformability index of specimens is reduced. However, adding geogrids led to significant increases in the failure and fracture strains. Comparing the strain–stress behaviour of untreated and lime-treated samples, which indicated ductile and brittle behaviours, respectively, the geogrid-lime-improved specimens proposed semi-ductile

behaviour. In addition, by adding geogrids, deformability index of specimens increased. Moreover, by increasing the MC, deformability index and failure strain of specimens increased.

(7) From the SEM test results, it was inferred that the unimproved clay characterised by several voids in random orders. However, the soil was cemented by lime due to the pozzolanic reactions and the sample demonstrated a well-structured matrix with almost no voids. However, increasing the MC led to the lime to be dissolved and decayed, and resulted in the crystals to be created with weak bonds among lime and soil particles. Moreover, it also formed many voids which led to a significant decrease in the geotechnical properties.

(8) From the simple prediction model, several equations were obtained based on the ratio of MC/lime content to reasonably estimate the geotechnical properties.

Acknowledgement

The authors would like to thank Prof. Togay Ozbakkaloglu for his valuable review and useful comments in the preparation of this manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was supported by the Laboratory of Soil and Concrete of Abadgaran Negin Jonoobshargh Company (ANJ Co.), Kerman, Iran. [grant number: 116/3C-1394].

ORCID

Jie Li http://orcid.org/0000-0002-0344-2707

References

AASHTO T 307. (2005). Standard method of test for determining the resilient modulus of soils and aggregate materials.

Afshar, A., Jahandari, S., Rasekh, H., Shariati, M., Afshar, A., & Shokrgozar, A. (2020). Corrosion resistance evaluation of rebars with various primers and coatings in concrete modified with different additives. *Construction and Building Materials*, *262,* 120034. https://doi.org/10.1016/j.conbuildmat.2020.120034

Al-Qadi, I. L., Dessouky, S. H., Kwon, J., & Tutumluer, E. (2008). Geogrid in flexible pavements: Validated mechanism. *Transportation Research Record*, *2045*(1), 102–109. https://doi.org/10.3141/2045-12

Ali, H., & Mohamed, M. (2018). The effects of lime content and environmental temperature on the mechanical and hydraulic properties of extremely high plastic clays. *Applied Clay Science*, *161*, 203–210. https://doi.org/10.1016/j.clay.2018.04.012

ASTM C618. (2015). *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*. ASTM International.

ASTM C977. (2000). *Standard specification for quicklime and hydrated lime for soil stabilization*. ASTM International.

ASTM D1557. (2007). *Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000ft-lbf/ft3 (2,700 kN-m/m3*. ASTM International.

ASTM D2216. (2010). *Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass*. ASTM International.

ASTM D2435M. (2011). *Standard test methods for one-dimensional consolidation properties of soils using incremental loading*. ASTM International.

ASTM D2487. (2011). *Standard practice for classification of soils for engineering purposes (unified soil classification system)*. ASTM International.

ASTM D422-63. (2002). *Standard method for particle-analysis of soils*. ASTM International.

ASTM D423-66. (1972). *Standard method of test for liquid limit of soils*. West Conshohocken: ASTM International.

ASTM D424-54. (1982). *Standard method of test for plastic limit*. ASTM International.

ASTM D5102. (2009). *Standard test methods for unconfined compressive strength of compacted soil-lime mixtures*. West Conshohocken: ASTM International.

ASTM D854. (2010). *Standard test methods for specific gravity of soil solids by water pycnometer*. West Conshohocken: ASTM International.

Avila, M. J. K., & Pantoja, J. D. C. (2018). Disaster mitigation from an analysis of a condemned building erected over collapsible clay soil in Brazil. *World Academy of Science, Engineering and Technology International Journal of Architectural and Environmental Engineering*, *12*(2).

Azadegan, O., Jafari, S. H., & Li, J. (2012). Compaction characteristics and mechanical properties of lime/cement treated granular soils. *Electronic Journal of Geotechnical Engineering*, *17*, 2275–2284.

Azadegan, O., Li, J., Jafari, S. H., & Ren, G. (2013). Geogrid reinforced lime cement treated granular soils. *Applied Mechanics and Materials*, *330*, 1090–1094. Trans Tech Publications. https://doi.org/10.4028/www.scientific.net/AMM.330.1090

Carlton, B. D., & Pestana, J. M. (2016). A unified model for estimating the in-situ small strain shear modulus of clays, silts, sands, and gravels. *Soil Dynamics and Earthquake Engineering*, *88*, 345–355. https://doi.org/10.1016/j.soildyn.2016.01.019

Chemeda, Y. C., Deneele, D., Christidis, G. E., & Ouvrard, G. (2015). Influence of hydrated lime on the surface properties and interaction of kaolinite particles. *Applied Clay Science*, *107*, 1–13. https://doi.org/10.1016/j.clay.2015.01.019

Cheshomi, A., Eshaghi, A., & Hassanpour, J. (2017). Effect of lime and fly ash on swelling percentage and Atterberg limits of sulfate-bearing clay. *Applied Clay Science*, *135*, 190–198. https://doi.org/10.1016/j.clay.2016.09.019

Cong, M., Longzhu, C., & Bing, C. (2014). Analysis of strength development in soft clay stabilized with cement-based stabilizer. *Construction and Building Materials*, *71*, 354–362. https://doi.org/10.1016/j.conbuildmat.2014.08.087

Consoli, N. C., Caberlon Cruz, R., Floss, M. F., & Festugato, L. (2010). Parameters controlling tensile and compressive strength of artificially cemented sand. *Journal of Geotechnical and Geoenvironmental Engineering*, *136*(5), 759–763. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000278

Das, B. M. (1979). *Introduction to soil mechanics*. Iowa State University Press.

Duncan, J. M., & Bursey, A. (2013). Soil modulus correlations. In *Foundation Engineering in the Face of Uncertainty: Honoring Fred H. Kulhawy* (pp. 321–336). https://doi.org/10.1061/9780784412763.026

Eyo, E. U., Ng'ambia, S., & Abbeyb, S. J. (2020). Performance of clay stabilized by cementitious materials and inclusion of zeolite/alkaline metals-based additive. *Transportation Geotechnics*, *23*, 100330. https://doi.org/10.1016/j.trgeo.2020.100330

Garzón, E., Cano, M., OKelly, B. C., & Sánchez-Soto, P. J. (2016). Effect of lime on stabilization of phyllite clays. *Applied Clay Science*, *123*, 329–334. https://doi.org/10.1016/j.clay.2016.01.042

Gholhaki, M., Hajforoush, M., & Kazemi, M. (2017). An investigation on the fresh and hardened properties of self-compacting concrete incorporating magnetic water with various pozzolanic materials. *Construction and Building Materials*, *158*, 173–180. https://doi.org/10.1016/j.conbuildmat.2017.09.135

Ghourchian, S., Wyrzykowski, M., & Lura, P. (2016). The bleeding test: A simple method for obtaining the permeability and bulk modulus of fresh concrete. *Cement and Concrete Research*, *89*, 249–256. https://doi.org/10.1016/j.cemconres.2016.08.016

Hajjaji, M., & Mleza, Y. (2014). Hydrated burnt clay–lime mixes: Effects of curing time and lime addition. *Applied Clay Science*, *101*, 177–183. https://doi.org/10.1016/j.clay.2014.07.033

Han, Z., & Vanapalli, S. K. (2016). Relationship between resilient modulus and suction for compacted subgrade soils. *Engineering Geology*, *211*, 85–97. https://doi.org/10.1016/j.enggeo.2016.06.020

Hobbs, D. W. (1971). The dependence of the bulk modulus, young's modulus, creep, shrinkage and thermal expansion of concrete upon aggregate volume concentration. *Matériaux et Construction*, *4*(2), 107–114. https://doi.org/10.1007/BF02473965

ISO/TS 13434. (2008). Geosynthetics-guidelines for the assessment of durability. International Organization for Standardization.

Jahandari, S., Li, J., Saberian, M., & Shahsavarigoughari, M. (2017a). Experimental study of the effects of geogrids on elasticity modulus, brittleness, strength, and stress-strain behavior of lime stabilized kaolinitic clay. *GeoResJ*, *13*, 49–58. https://doi.org/10.1016/j.grj.2017.02.001

Jahandari, S., Saberian, M., Tao, Z., Mojtahedi, S. F., Li, J., Ghasemi, M., & Li, W. (2019). Effects of saturation degrees, freezing-thawing, and curing on geotechnical properties of lime and lime-cement concretes. *Cold Regions Science and Technology*, *160*, 242–251. https://doi.org/10.1016/j.coldregions.2019.02.011

Jahandari, S., Saberian, M., Zivari, F., Li, J., Ghasemi, M., & Vali, R. (2017c). Experimental study of the effects of curing time on geotechnical properties of stabilized clay with lime and geogrid. *International Journal of Geotechnical Engineering*, *13*(2), 172–183. https://doi.org/10.1080/19386362.2017.1329259

Jahandari, S., Toufigh, M. M., Li, J., & Saberian, M. (2017b). Laboratory study of the effect of degrees of saturation on lime concrete resistance due to the groundwater level increment. *Geotechnical and Geological Engineering*, *36*(1), 413–424. https://doi.org/10.1007/s10706-017-0335-4

Jha, A. K., & Sivapullaiah, P. V. (2015). Susceptibility of strength development by lime in gypsiferous soil—A micro mechanistic study. *Applied Clay Science*, *115*, 39–50. https://doi.org/10.1016/j.clay.2015.07.017

Keramatikerman, M., Chegenizadeh, A., & Nikraz, H. (2016). Effect of GGBFS and lime binders on the engineering properties of clay. *Applied Clay Science*, *132*, 722–730. https://doi.org/10.1016/j.clay.2016.08.029

Khemissa, M., & Mahamedi, A. (2014). Cement and lime mixture stabilization of an expansive overconsolidated clay. *Applied Clay Science*, *95*, 104–110. https://doi.org/10.1016/j.clay.2014.03.017

Li, J., Saberian, M., & Nguyen, B. T. (2018). Effect of crumb rubber on the mechanical properties of crushed recycled pavement materials. *Journal of Environmental Management*, *218*, 291–299. https://doi.org/10.1016/j.jenvman.2018.04.062

Little, D. N. (1995). Stabilization of pavement subgrades and base courses with lime.

Miao, Y., Huang, Y., Zhang, Q., & Wang, L. (2016). Effect of temperature on resilient modulus and shear strength of unbound granular materials containing fine RAP. *Construction and Building Materials*, *124*, 1132–1141. https://doi.org/10.1016/j.conbuildmat.2016.08.137

Mirzababaei, M., Miraftab, M., Mohamed, M., & McMahon, P. (2013). Unconfined compression strength of reinforced clays with carpet waste fibers. *Journal of Geotechnical and Geoenvironmental Engineering*, *139*(3), 483–493. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000792

Ouhadi, V. R., & Yong, R. N. (2003). The role of clay fractions of marly soils on their post stabilization failure. *Engineering Geology*, *70*(3–4), 365–375. https://doi.org/10.1016/S0013-7952(03)00104-2

Park, S. S. (2011). Unconfined compressive strength and ductility of fiber-reinforced cemented sand. *Construction and Building Materials*, *25*(2), 1134–1138. https://doi.org/10.1016/j.conbuildmat.2010.07.017

Péterfalvi, J., Primusz, P., Markó, G., Kisfaludi, B., & Kosztka, M. (2015). Evaluation of the effect of lime-stabilized subgrade on the performance of an experimental road pavement. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering*, *36*(2), 269–282.

Pooni, J., Giustozzia, F., Roberta, D., Setungea, S., & O'Donnell, B. (2019). Durability of enzyme stabilized expansive soil in road pavements subjected to moisture degradation. *Transportation Geotechnics*, *21*, 100255. https://doi.org/10.1016/j.trgeo.2019.100255

Portland Cement Association. (1956). *Soil-cement laboratory handbook*.

Rahgozar, M., & Saberian, M. (2016). Geotechnical properties of peat soil stabilized with shredded waste tyre chips. *Mires and Peat*, *18*(3), 1–12.

Rahgozar, M. A., & Saberian, M. (2015). Physical and chemical properties of two Iranian peat types. *Mires and Peat*, *16*(7), 1–17.

Rai, R., Khandelwal, M., & Jaiswal, A. (2012). Application of geogrids in waste dump stability: A numerical modeling approach. *Environmental Earth Sciences*, *66*(5), 1459–1465. https://doi.org/10.1007/s12665-011-1385-1

Rajesh, S., & Viswanadham, B. V. S. (2009). Evaluation of geogrid as a reinforcement layer in clay based engineered barriers. *Applied Clay Science*, *46*(2), 153–165. https://doi.org/10.1016/j.clay.2009.07.019

Rao, S. M., Reddy, B. V. V., & Muttharam, M. (2001). The impact of cyclic wetting and drying on the swelling behaviour of stabilized expansive soils. *Engineering Geology*, *60*(1-4), 223–233. https://doi.org/10.1016/S0013-7952(00)00103-4

Saberian, M., Jahandari, S., Li, J., & Zivari, F. (2017). Effect of curing, capillary action, and groundwater level increment on geotechnical properties of lime concrete: Experimental and prediction studies. *Journal of Rock Mechanics and Geotechnical Engineering*, *9*(4), 638–647. https://doi.org/10.1016/j.jrmge.2017.01.004

Saberian, M., Li, J., & Cameron, D. (2019). Effect of crushed glass on behavior of crushed recycled pavement materials together with crumb rubber for making a clean Green base and subbase. *Journal of Materials in Civil Engineering*, *31*(7), 04019108. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002765

Saberian, M., Li, J., Nguyen, B. T., & Boroujeni, M. (2020). Experimental and analytical study of dynamic properties of UGM materials containing waste rubber. *Soil Dynamics and Earthquake Engineering*, *130*, 105978. https://doi.org/10.1016/j.soildyn.2019.105978

Saberian, M., Mehrinejad Khotbehsara, M., Jahandari, S., Vali, R., & Li, J. (2017). Experimental and phenomenological study of the effects of adding shredded tire chips on geotechnical properties of peat. *International Journal of Geotechnical Engineering*, *12*(4), 347–356. https://doi.org/10.1080/19386362.2016.1277829

Saberian, M., & Rahgozar, M. A. (2016). Geotechnical properties of peat soil stabilized with shredded waste tyre chips in combination with gypsum, lime or cement. *Mires and Peat*, *18*(16), 1–16. https://doi.org/10.19189/MaP.2015.OMB.205

Saberian, M., Shi, L., Sidiq, A., Li, J., Setunge, S., & Li, C. Q. (2019). Recycled concrete aggregate mixed with crumb rubber under elevated temperature. *Construction and Building Materials*, *222*, 119–129. https://doi.org/10.1016/j.conbuildmat.2019.06.133

Sadeghian, F., Haddad, A., Jahandari, S., Rasekh, H., & Ozbakkaloglu, T. (2020). Effects of electrokinetic phenomena on the load-bearing capacity of different steel and concrete piles: A small-scale experimental study. *Canadian Geotechnical Journal*, *58*(5). https://doi.org/10.1139/cgj-2019-0650.

Sadrossadat, E., Heidaripanah, A., & Osouli, S. (2016). Prediction of the resilient modulus of flexible pavement subgrade soils using adaptive neuro-fuzzy inference systems. *Construction and Building Materials*, *123*, 235–247. https://doi.org/10.1016/j.conbuildmat.2016.07.008

Salimi, M., & Ghorbani, A. (2020). Mechanical and compressibility characteristics of a soft clay stabilized by slag-based mixtures and geopolymers. *Applied Clay Science*, *184*, 105390. https://doi.org/10.1016/j.clay.2019.105390

Selvadurai, A. P. S., & Katebi, A. (2013). Mindlin's problem for an incompressible elastic half-space with an exponential variation in the linear elastic shear modulus. *International Journal of Engineering Science*, *65*, 9–21. https://doi.org/10.1016/j.ijengsci.2013.01.002

Sherwood, P. (1993). Soil stabilization with cement and lime.

Sirivitmaitrie, C., Puppala, A. J., Saride, S., & Hoyos, L. (2011). Combined lime–cement stabilization for longer life of low-volume roads. *Transportation Research Record*, *2204*(1), 140–147. https://doi.org/10.3141/2204-18

Soltani, A., Deng, A., & Taheri, A. (2018). Swell–compression characteristics of a fiber–reinforced expansive soil. *Geotextiles and Geomembranes*, *46*(2), 183–189. https://doi.org/10.1016/j.geotexmem.2017.11.009

Sun, D. A., Zhang, L., Li, J., & Zhang, B. (2015). Evaluation and prediction of the swelling pressures of GMZ bentonites saturated with saline solution. *Applied Clay Science*, *105–106*, 207–216. https://doi.org/10.1016/j.clay.2014.12.032

Tang, C., Shi, B., Gao, W., Chen, F., & Cai, Y. (2007). Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. *Geotextiles and Geomembranes*, *25*(3), 194–202. https://doi.org/10.1016/j.geotexmem.2006.11.002

Thompson, M. R. (1966). *Shear strength and elastic properties of lime soil mixtures*. Highway Research Board, University of Illinois, Champaign, (pp.–14).

Yong, R. N., & Ouhadi, V. R. (2007). Experimental study on instability of bases on natural and lime/cement-stabilized clayey soils. *Applied Clay Science*, *35*(3–4), 238–249. https://doi.org/10.1016/j.clay.2006.08.009

Zhu, H., Ma, Y., Liu, Y. X., & Wang, J. (2009). Application of the geogrid reinforced soil retaining walls for a high slope supporting project. In *Geosynthetics in Civil and Environmental Engineering* (pp. 266–270). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-69313-0_51