7-28-2017

Cement Improved Highly Weathered Phyllite for Highway Subgrades: A Case Study in Shaanxi Province.

Xuesong Mao
Chang'an University, xuesongxian@aliyun.com

Carol Jean Miller
Wayne State University, cmiller@eng.wayne.edu

Longqi Liu
Chang'an University

Journal of Traffic and Transportation Engineering (English Edition) 2017; 4 (4): 403–411

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jtte

Original Research Paper

Cement improved highly weathered phyllite for highway subgrades: A case study in Shaanxi province

Xuesong Mao [a,*], *Carol Jean Miller* [b], *Longqi Liu* [a]

[a] *School of Highway, Chang'an University, Xi'an 710064, China*

[b] *Department of Civil and Environmental Engineering, Wayne State University, Detroit, MI 48105, USA*

HIGHLIGHTS

- Weathered phyllite belonged to soft rock, and its property was easily affected by the water.
- The resilient modulus and deflection were analyzed with the cement content increasing.
- Water content and soaking time are key factors affecting the seepage depth and resilient modulus.
- The recommend values for cement addition and water content are given out.

ARTICLE INFO

Article history:
Received 18 March 2017
Received in revised form
8 May 2017
Accepted 9 May 2017
Available online 28 July 2017

Keywords:
Highly-weathered phyllite
Cement admixture
Soaking time
Wetting deformation
Resilient modulus

ABSTRACT

In a cost-saving move, the soft rocks composed of highly-weathered phyllites available on-site were used to fill the subgrade in the eastern Ankang section of the expressway of Shiyan to Tianshui, China. Cement admixture was used to improve the performance of the weathered phyllites. In order to determine the best mix ratio, values corresponding to compaction performance, unconfined compressive strength, and the California bearing ratio (CBR) were analyzed for variable cement content weight percentages (3%, 4%, 5%, and 6%) using test subgrade plots in the field. Field measurements of resilience modulus and deflection confirmed that the strength of the subgrade increased as the cement ratio increased. In order to further evaluate the cement/phyllite mixture, the performance of the 3% cement ratio sample was evaluated under saturated conditions (with various levels of moisture addition and soaking time) using both the wetting deformation and resilient modulus values. Results suggest that moisture added and soaking time are key factors that affect the seepage depth, water content, and resilient modulus. The recommend values for the cement addition and for the water content are given out. This study can aid in prevention of highway damage by improving the foundation capacity and lengthening the lifecycle of the highway in phyllite distributed region at home and abroad.

* *Corresponding author*. Tel./fax: +86 29 82334869.
E-mail address: xuesongxian@aliyun.com (X. Mao).

Peer review under responsibility of Periodical Offices of Chang'an University.
http://dx.doi.org/10.1016/j.jtte.2017.07.003

1. Introduction

The rocks along the eastern Ankang section of the highway from Shiyan to Tianshui are primarily composed of weathered phyllite. The phyllite rocks in this region are severely weathered, with very low strength. However, due to the absence of other favorable alternatives for subgrade material for highway construction, the weathered phyllite was selected for this purpose. The weathered phyllite is belonged to soft rocks according to the mechanical properties. Soft rocks are critical geotechnical materials since they present several undesirable behaviors, such as low strength, disaggregation, crumbling, high plasticity, slaking, fast weathering, and many other characteristics.

In recent years, the use of soft rocks has been geomaterials investigated from physical, mechanical, classification, and other aspects at home and abroad. In China, Zhou et al. (2003) has discussed mechanical properties of several typical types of soft rock in south China which contain red sandstone, mudstone, and black carbonaceous mudstone. Zheng et al. (2005), Zhao et al. (2005), Nie et al. (2008), and Qing et al. (2006) studied the feasibility of using soft rock as filling material for highway and railway systems. Liu et al. (2006), Wang et al. (2011) studied the wetting deformation of the soft rock under laboratory conditions. Pu et al. (2017) carried out the study on rupture and energy characteristics of phyllites under triaxial compression. Yang et al. (2010) studied the deformation characteristics of roadbed filling of soft metamorphic rock before and after soaking by compression tests in Qinling—Bashan mountainous region. Mao et al. (2012), Zhang et al. (2014a) carried out the experimental study on subgrade filling material of phyllite spoil improved with cement. Xin et al. (2014), Guo et al. (2014), Zhang et al. (2014b), He and Zhang (2014) studied the geomechanical and water vapor absorption characteristics properties characterization of deep soft rocks with experiments. Mao et al. (2016, 2017) analyzed the moisture migration mechanism of strongly weathered phyllite subgrade filling and studied factors influencing modified phyllite stuffing CBR value. Qiu et al. (2017) discussed the dynamic failure of a phyllite with a low degree of metamorphism under impact of Brazilian test.

Foreign researchers also have done some experiments on the soft rock. By experiments and modeling, Ramamurthy et al. (1993) and Arnold et al. (2001) studied the sorption behavior of U(VI) on phyllite. Mohamed et al. (2007) developed the e-SSC test, and established a systematic and computerized testing method with laboratory procedure to quantify the shrink and swell characteristics of soft rock for classification. Manasseh and Olufemi (2008) analyzed the effect of lime on some geotechnical properties of Igumale shale. Adom-Asamoah and Afrifa (2010), Sadisun et al. (2002), Bornert et al. (2010), Nara et al. (2012), Yang et al. (2012), and Nahazanan et al. (2013), studied the hydro mechanical behavior of the soft rock, such as the elastic properties, the shear strength, the shrinkage and swelling induced by suction variation. Ulusay and Erguler (2012) evaluated the method to predict the strength of weak and soft rocks using the needle penetration test. Besides, Ulusay and Erguler (2012) also evaluated the soft rock performance and possible uses by needle penetration test. Regmi et al. (2012) did the research on the effect of rock weathering, clay mineralogy, and geological structures in the formation of large landslide, and applied the method for the Dumre Besei landslide, Lesser Himalaya Nepal. Cantarero et al. (2014) investigated the fluid flow in fractures and host rocks in shallow buried Miocene alluvial fan deposits. Giambastiani (2014) carried out the study of soft rocks in Argentina and gave out the category according to the clastic sedimentary rocks and pyroclastic volcanic rocks. Garzón et al. (2010, 2016) studied the physical and geotechnical properties of clay phyllites and researched the effect of lime on stabilization of phyllite clays.

From the previous analysis above, it is clear that there is a knowledge gap relating to soft rock improvement technology for subgrade fill. There was quite little research about using the phyllite as the subgrade filling material at home and abroad. The present investigation, described in this paper, describes the use of cement admixture to improve the performance of weathered phyllite as subgrade fill. The field performance of the improved fill was evaluated based on the measured resilience, deflection, and wetting deformation. This evaluation confirms the feasibility of using the improved weathered phyllite as a subgrade material.

2. Experimental evaluation

2.1. *Mineral component of phyllite*

The rocks along the eastern Ankang section of the highway from Shiyan to Tianshui are primarily composed of weathered phyllite as shown in Fig. 1. The mineral composition of the weathered phyllite is shown in Table 1. The main mineral components of the rock are quartz and mica, at 42% and 50% composition by weight, respectively. The quartz and

Fig. 1 – Highly weathered phyllite near the highway construction site.

Table 1 – Mineral composition of the weathered phyllite.

Mineral composition	Weight percent (%)
Quartz	41–43
Muscovite	46–49
Biotite	3–5
Garnet	3–5
Hematite	2–3

muscovite was distributed irregularly with small amounts of biotite and muscovite in the quartz block. The quartz is a granular alterative non-directional crystal structure with a grain size 0.1–0.4 mm. The biotite had a red to light brown color and a schistic structure with a grain size ranging from 0.5 to 1.0 mm. The muscovite aggregation has a metacrystal texture with grain size ranging between 0.1 and 0.5 mm. There was a small amount of quartz and opaque metal mineral among the muscovite. Existing research (Shu, 2008) suggests that the amount and the structure of mica affect the strength of the phyllite. The mica is easily smashed with soaking, which leads to a large deformation of the subgrade.

2.2. Uniaxial compressive strength of phyllite

The uniaxial compressive strength of the weathered phyllite was determined using the Test Methods of Rock for Highway Engineering (JTG E41-2005). The uniaxial compressive strength of natural state ranged between 15.31 MPa and 17.94 MPa. The uniaxial compressive strength of saturated state ranged between 4.29 MPa and 4.61 MPa. The softening coefficient ranged from 0.26 to 0.28. The weathered phyllite is classified as soft rock because the softening coefficient was smaller than 0.3, and the uniaxial compressive strength of the saturated state was smaller than 5 MPa. The softening effect of the rock is very strong. If the weathered phyllite was used "as it is" to fill the subgrade, the change in strength and deformation must be considered, especially during saturating conditions.

2.3. Particle-size analysis

Samples of weathered phyllite filling material from three different locations at the field section (K22 + 800) in BAIHE County were collected and the particle-size analysis was performed. The grain size distribution is shown in Fig. 2.

In order to evaluate the graduation of soil, the coefficient of uniformity C_u and the coefficient of curvature C_c were determined as follows

$$C_u = d_{60}/d_{10} \tag{1}$$

$$C_c = d_{30}^2/d_{60}d_{10} \tag{2}$$

where d_{10}, d_{30}, d_{60} are the particle diameters associated with 10%, 30%, and 60% passing, respectively.

A soil with coefficient of curvature between 1 and 3 is considered to be well graded as long as the coefficient of uniformity is also greater than 4. The evaluation of grade is

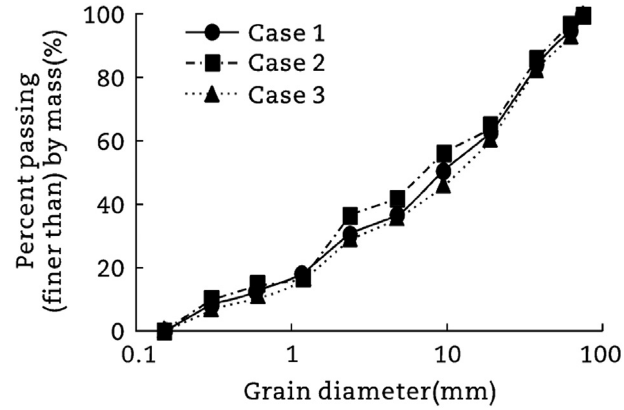

Fig. 2 – Grain size distribution of weathered phyllite filling material.

shown in Table 2, with the weathered phyllite classified as poorly graded – signifying unsuitability as subgrade material.

2.4. Optimum water rate and the maximum dry density

According to Test Methods of Soils for Highway Engineering (JTG E40-2007), the compaction test was performed. Under the weight II compaction method, the optimum water rate was 6.8% and the maximum dry density was 2.45 g/cm^3.

2.5. California bearing ratio test

According to Test Methods of Soils for Highway Engineering (JTG E40-2007), the California bearing ratio (CBR) test was performed. The specimen was made under the optimum water rate and then saturated in the water for 96 h. The test samples were collected at 6 different sections of the field site. CBR results are displayed in Table 3.

The CBR value of the filler material of the subgrade should be greater than 3% according to Specification for Design of Highway Asphalt Pavement (JTG D50-2006). As shown in Table 3, it was determined that some of the material would not meet this specification. The phyllite material was used to fill the subgrade directly when CBR was determined to equal or exceed 3% CBR criteria; when the CBR was less than 3%, the material was set aside for material improvement using the cement admixture. The present research evaluated the use of 3%, 4%, 5%, and 6% cements (by weight) with the weathered phyllite using measurements of the strength characteristics of the improved materials.

Table 2 – Size distribution characteristics of weathered phyllite filling material.

No.	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	C_u	C_c	Grade
1	0.43	2.36	16.77	39.42	0.7807	Poorly
2	0.40	2.27	15.81	40.04	0.8273	Poorly
3	0.55	2.80	18.91	34.69	0.7617	Poorly

Table 3 – Results of CBR test.

Test section	K54 + 440	K54 + 470	K54 + 490	K54 + 500	K54 + 510	K54 + 520
CBR (%)	2.60	2.21	2.77	3.20	2.61	2.98

3. Evaluation of the cement improved filling material

3.1. *Compaction test*

From the sieve test of weathered phyllite filling material, it was known the grain diameter between 5 mm and 38 mm accounted for approximately 60% of the material weight. According to Test Methods of Soils for Highway Engineering (JTG E40-2007), the weight II compaction method was adopted, the dry density and water content used in the compaction process shown in Table 4. And then the optimum water rate and maximum dry density were got in Fig. 3. The max dry density and the optimum water content are directly related to the cement content, as an increase in cement admixture impacts more of the filler, which then demands more moisture to complete the hydration reaction. So, the optimum water rate decreased with the more cement content.

3.2. *Unconfined compression strength*

The unconfined compression strength test was completed using the specifications of Test Methods of Soils for Highway Engineering (JTG E40-2007). According to the Specification for Design Highway Subgrade (JTG D30-2015), the degree of compaction in roadbed needs to reach 96%. The test specimens were constructed at a optimum moisture content, with a 96% degree of compaction. The unconfined compression strength as a function of time was determined for each of the cement additive contents as shown in Fig. 4. The unconfined compression strength was directly related to cement content, although the magnitude of the increase in unconfined compression strength was variable. For example, at the 7th day the 4% cement content sample increased by 20.5% in unconfined compression strength compared to the 3% sample. However, the increase for the 5% and 6% samples was 140% and 263%, respectively.

As shown in Fig. 4, the improved weathered phyllite had high early strength, which improved further with age. The strength increased most rapidly in the first 7 days. The unconfined compression strength at this age has attained around 70% and 90% of the 28 days strength. Therefore, the first 7 days of curing are critical. The degree of compaction obtained was shown in Table 5. The degree of compaction could meet the demand of specification.

Table 4 – Dry density and water content used in the compaction process.

Water content (%)	Dry densities with different cement contents (g/cm^3)			
	3%	4%	5%	6%
5.0	2.08	2.11	2.09	2.12
5.5	2.13	2.14	2.13	2.14
6.0	2.17	2.16	2.15	2.11
6.5	2.19	2.18	2.12	2.08
7.0	2.19	2.13	2.08	2.05
7.5	2.15	2.09	2.04	2.01

3.3. *California bearing ratio*

Test specimens were prepared for cement content ratios of 3%, 4%, 5%, and 6%. The California bearing ratio (CBR) test was performed according to Test Methods of Soils for Highway Engineering (JTG E40-2007). The resulting data is shown in Fig. 5.

The data in Fig. 5 suggests that CBR of the improved weathered phyllite is sufficient for the design demands. In fact, at the lowest admixture ratio (3%) the CBR reached a value of 7.8%. Higher cement content caused an even more significant increase in CBR. The fillers with 4%, 5%, and 6% cement contents showed improvement in CBR of 35.9%, 114.1%, and 150%, respectively as compared to the 3% cement content.

4. Mechanical properties of the improved filler

In order to evaluate the mechanical properties of subgrade, a 200 m test subgrade, from K22 + 720 to K22 + 920, was built using weathered phyllite fill materials with 3%, 4%, 5%, and 6% cement contents.

4.1. *Site resilience modulus*

The site bearing plate test was performed as specified in Field Test Method of Subgrade and Pavement for Highway Engineering (JTG E60-2008). The resulting relation between resilience modulus and cement content is presented in Fig. 6.

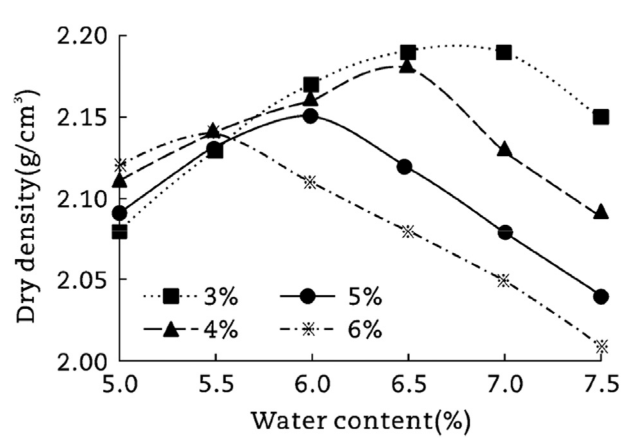

Fig. 3 – Compaction results of four cement contents.

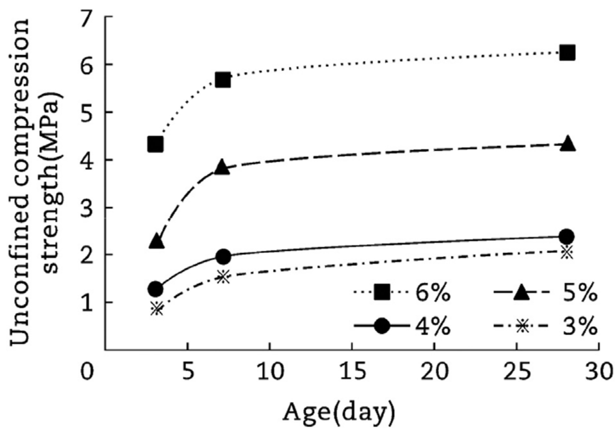

Fig. 4 – Time dependence of unconfined compression strength.

As cement content increases, the resilience modulus of the subgrade also increases in a nearly linear fashion. With a cement content of 3%, the resilience modulus of the subgrade is 66.42 MPa. As the cement content increases, the resilience modulus increases significantly. For example, the resilience moduli of the 4%, 5%, and 6% cement subgrades increase by 18.4%, 35.2%, and 58.7% respectively over the 3% installation. The resilience modulus of the subgrade must be greater than or equal to 30 MPa for the expressway or first-class highway, according to the Specification for Design of Highway Asphalt Pavement (JTG D50-2006). Clearly, following the cement addition to the weathered phyllite, the resilience modulus meets the specification demand.

4.2. *Site deflection test*

The deflection of subgrade and the deflection of the pavement were the most important indicators to reflect the overall quality of subgrade and pavement. Following the specifications of the Field Test Method of Subgrade and Pavement for Highway Engineering (JTG E60-2008), the Backman beam method was used to complete the site deflection of the subgrade which was combined with various cement ratios at 7 days of curing. The dependence of deflection on cement content is provided in Fig. 7. The data confirms that increasing cement composition improves the performance of the subgrade as evidenced by decreases in deflection (increase in bearing capacity).

Table 5 – Degree of compaction in the unconfined compression strength test.

Cement content (%)	Dry density (g/cm^3)		Maximum dry density (g/cm^3)	Degree of compaction (%)
	Test value	Average		
3	2.01	2.15	2.19	98.0
	2.29			
	2.14			
4	2.42	2.10	2.18	96.3
	2.00			
	1.89			
5	1.99	2.09	2.15	97.2
	2.02			
	2.27			
6	1.95	2.09	2.14	97.6
	2.25			
	2.16			

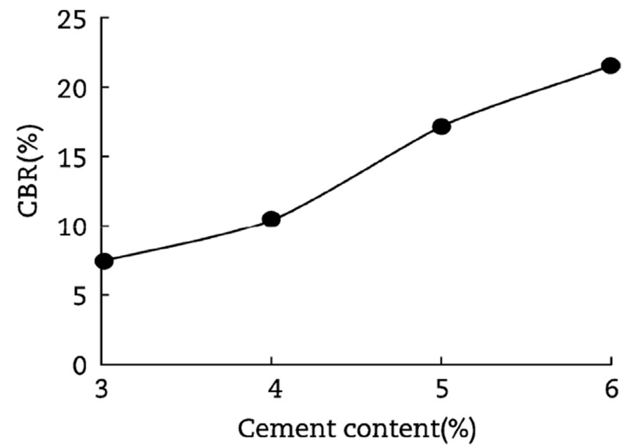

Fig. 5 – CBR dependence on cement content.

5. Impact of excess moisture additions

In order to determine the impact of excess moisture on the strength and the deformation characteristics of the subgrade, the field loading plate test was done on the 3% cement improved weathered phyllite subgrade mixture prior to, and following, the inundation.

5.1. *Test plan*

Two test sections with 3% cement improved subgrade were used for this investigation. A separation of 20 m was provided between the two sections. There are 6 test points in each section, with two groups in each section as shown in Fig. 8. The two key variables in this part of the investigation were

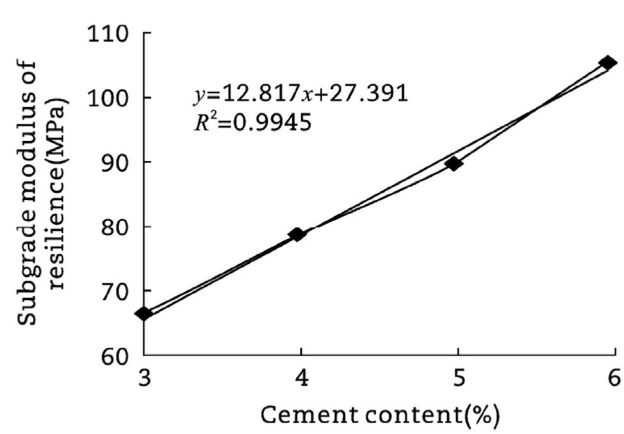

Fig. 6 – Relation between resilience modulus and cement content.

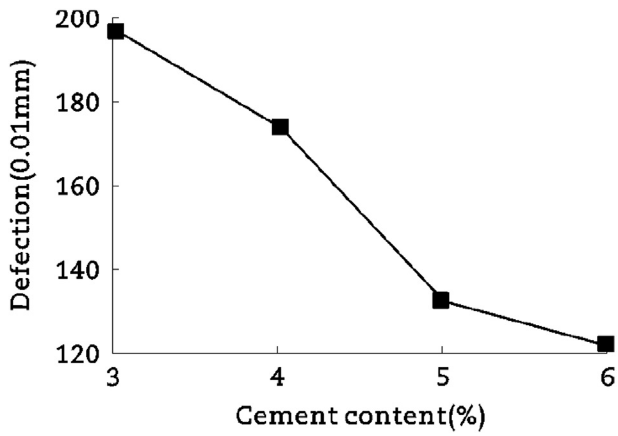

Fig. 7 – Subgrade deflection and cement content.

the amount of added water and the soaking time. The test plan is provided in Table 6.

5.2. *Measurement of deformation properties*

The wetting deformation and the wet deformation rate were used to evaluate the change of deformation properties. The state of subgrade before soaking was the dry state, and after soaking was the wet state. The wetting deformation was calculated as the difference between the accumulative rebound deformation of subgrade between dry and wet states at each stage of loading. Wetting deformation rate was calculated as the ratio between the wetting deformation and the accumulative rebound deformation of dry state were expressed as

Table 6 – Experimental design of soaking investigation.

Test group	Water added (L)	Soaking time (h)
a	50	12
b	100	12
c	50	24
d	100	24

$$\epsilon = \sum l_{iD} - \sum l_{iW} \tag{3}$$

$$\delta = \frac{\epsilon}{\sum l_{iD}} \tag{4}$$

where ϵ is wetting deformation (mm), l_{iD} is rebound deformation of subgrade in dry state at each stage of loading (mm), l_{iW} is rebound deformation of subgrade in wet state for each stage of loading (mm), δ is wetting deformation rate (%).

In order to avoid the variability of every testing site, the results of the test using the average value of each testing group were analyzed.

The data of Fig. 9 suggest that the rebound deformation under dry state was nearly same for all points. When the soaking time was same, for condition a and condition b as one group, condition c and d as one group, the wetting deformation increased with the amount of soaking water. When the amount of water was same, for condition a and condition c as one group, condition b and d as one group, the wetting deformation increased with the soaking time.

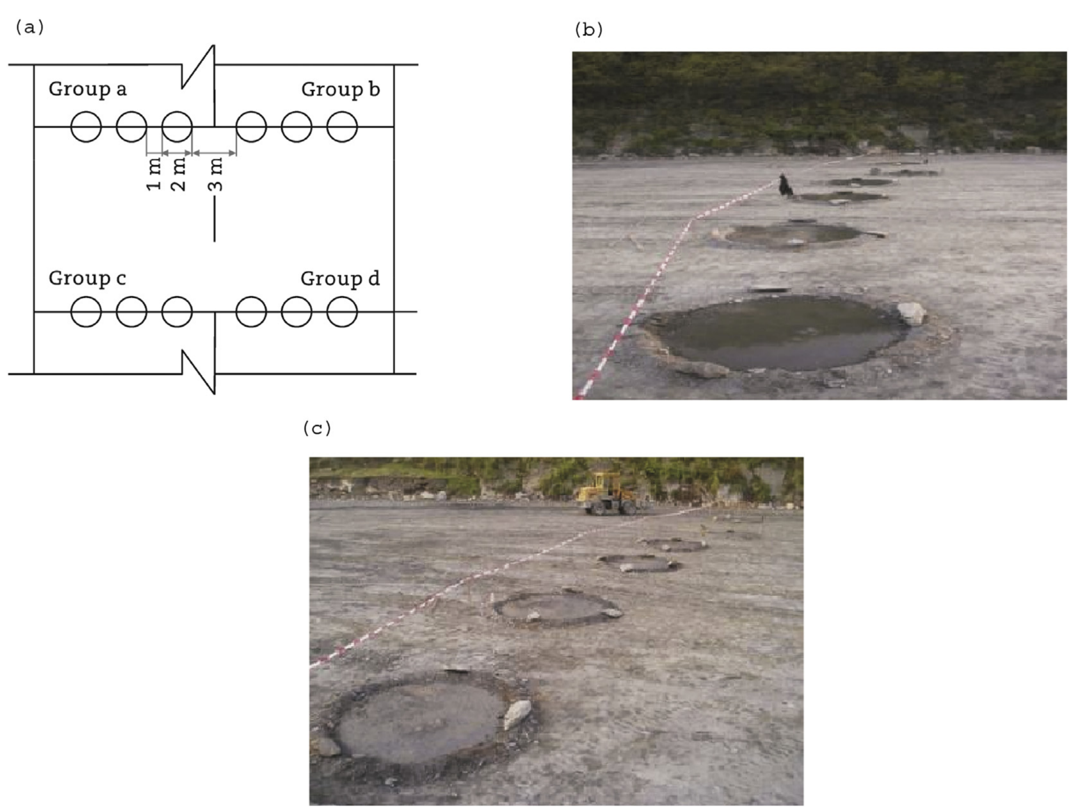

Fig. 8 – Plan view of test layout. (a) Test layout. (b) Water addition. (c) After soaking.

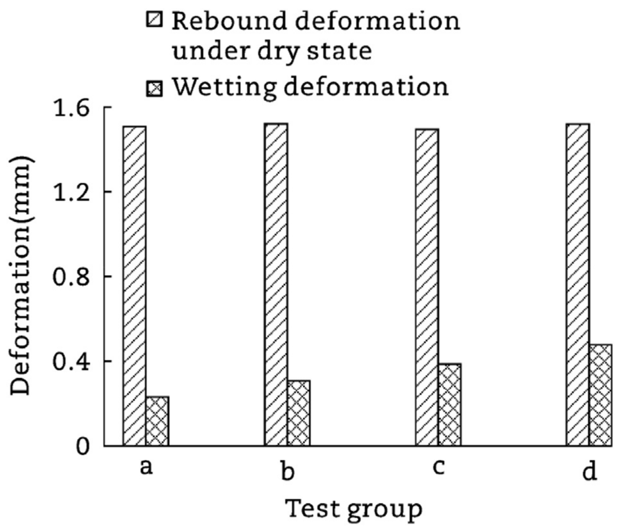

Fig. 9 – Deformation of subgrade under wet and dry conditions.

Both the amount of water and soaking time affected the wetting deformation and soaking time showed the greatest influence.

5.3. *Water content of subgrade*

Water content at various depths of the subgrade was determined according to Test Methods of Soils for Highway Engineering (JTG E40-2007). The resulting relation between water content and depth for various test conditions is presented in Fig. 10. As demonstrated in this Figure, the initial condition corresponds to a nearly uniform moisture distribution over depth. After soaking, the subgrade water content increased. With increasing depth, the water content decreased. From 0 to 30 cm, the water content response was essentially the same, with soils close to saturation. With increasing depth, the water content changed. When the soaking time was same, for condition a and condition b as one group, condition c and d as one group, the water content increased with the amount of soaking water. When the amount of water was same, for condition a and condition c as one group, condition b and d as one group, the water content increased with the soaking time. Both the soaking time and the amount of water were the factors to affect the water content, and the soaking time was more important. For example, for the amount of water was 50 L or 100 L, after 12 h soaking, the depth of water penetration was 60 cm; after 24 h soaking, the depth of water penetration was 70 cm.

The wetting deformation was plotted as a function of water penetration. As shown in Fig. 11, the wetting deformation was directly proportional to amount of water penetration, and with water penetration increase.

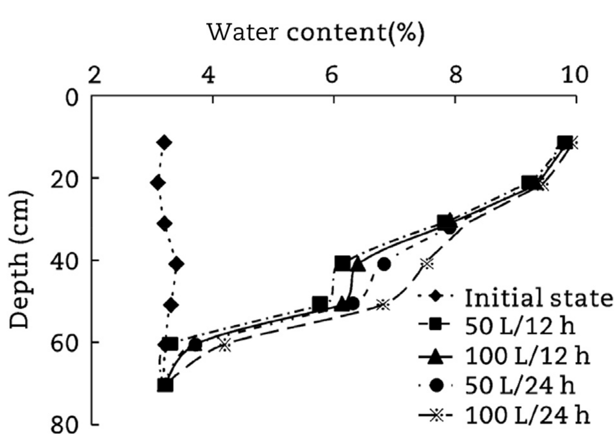

Fig. 10 – Water content profile for different soaking volumes and times.

5.4. *Decay of site resilience modulus*

It is known that wetting deformation can induce bearing capacity decay. To investigate this for the present study, we obtained the site resilience modulus for different conditions as shown in Table 7.

As suggested in Table 7, the site resilience modulus was affected by both the amount of water and the soaking time. At the initial state, the site resilience modulus was nearly uniform. As the amount of water and the soaking time increased, the decay rate of site resilience modulus increased. In the worst condition d, although the decay rate of site resilience modulus was 25.5%, the site resilience modulus was still 53.8 MPa, which meets the subgrade demand in the Specification for Design of Highway Asphalt Pavement (JTG D50-2006). Under the situation that the grain diameter between 5 mm and 38 mm accounted for

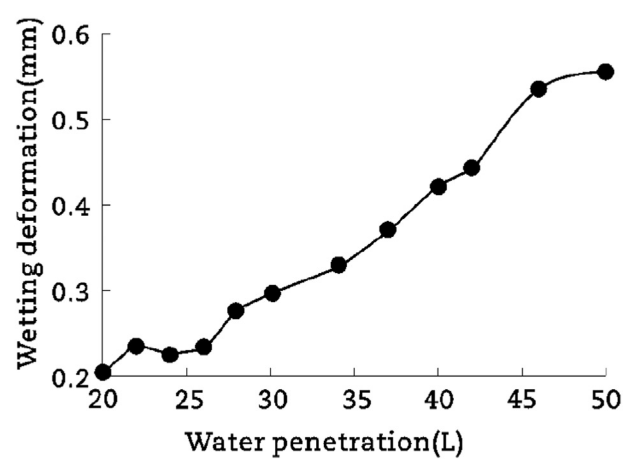

Fig. 11 – Wetting deformation as function of water penetration.

Table 7 – Site resilience modulus before and after soaking.

Test group	a	b	c	d
Before soaking	76.7	76.9	72.4	72.6
After soaking	64.0	63.1	57.0	53.8
Decay rate	16.5	18.2	21.3	25.5

approximately 60% of the material weight, the recommend value for the cement addition is 3% and for the water content is 5.7%. The experiments can aid in prevention of highway damage by improving the foundation capacity and lengthen the lifecycle of the highway in phyllite distributed region at home and abroad.

6. Conclusions

1) The results of electron microscope analysis and uniaxial compressive strength test of the original weathered phyllite showed that the rock belonged to the category of soft rock, and its property was easily affected by the water.
2) Particle-size analysis and California bearing ratio (CBR) with the weathered phyllite filler material showed the material was bad grade and the CBR can't meet the demand of Specification for Design of Highway Asphalt Pavement (JTG D50-2006).
3) The indoor experiments of cement improved weathered phyllite filler showed the maximum dry density and optimum water content increased with the amount of cement increased, the unconfined compression strength and CBR value significantly increased with the amount of cement increased under the test condition.
4) Mechanical property of the field test showed that the resilience modulus of the subgrade was linearly increased with the cement content increasing; the site deflection was decreased the cement content increase.
5) The water content and the soaking time were the key factors to affect the mechanical property of subgrade. Wetting deformation was directly proportional to the amount of water penetration, and wetting deformation resulted in decay of the site resilience modulus.
6) Under the situation that the grain diameter between 5 mm and 38 mm accounted for approximately 60% of the material weight, the recommend value for the cement addition is 3%, and for the water content is 5.7%.

Acknowledgments

We acknowledge the support of National Natural Science Foundation of China (51378072) and Special Fund for Basic Scientific Research of Central Colleges, Chang'an University (310821162012, 310821161023). The authors gratefully acknowledged their financial support.

REFERENCES

Arnold, T., Zorn, T., Zänker, H., et al., 2001. Sorption behavior of U(VI) on phyllite: experiments and modeling. Journal of Contaminant Hydrology 47 (2–4), 219.

Adom-Asamoah, M., Afrifa, R.O., 2010. A study of concrete properties using phyllite as coarse aggregates. Materials & Design 31 (9), 4561–4566.

Bornert, M., Valès, F., Gharbi, H., et al., 2010. Multiscale full-field strain measurements for micromechanical investigations of the hydromechanical behavior of clayey rocks. Strain 46 (1), 33–46.

Cantarero, I., Zafra, C.J., Travé, A., et al., 2014. Fracturing and cementation of shallow buried Miocene proximal alluvial fan deposits. Marine and Petroleum Geology 55, 87–99.

Garzón, E., Cano, M., O'Kelly, B.C., et al., 2016. Effect of lime on stabilization of phyllite clays. Applied Clay Science 123, 329–334.

Giambastiani, M., 2014. Soft rocks in Argentina. International Journal of Mining Science and Technology 24 (6), 883–892.

Garzón, E., Sánchez-Soto, P.J., Romero, E., 2010. Physical and geotechnical properties of clay phyllites. Applied Clay Science 48 (3), 307–318.

Guo, Y.C., Shen, A., Gao, T., et al., 2014. Road performance test and weathering degree evaluation of weathered rock subgrade filling. Journal of Traffic and Transportation Engineering 14 (3), 15–23.

He, M., Zhang, N., 2014. Experimental study on water absorption and strength degradation effect of shale at great depth. Disaster Advance 7 (3), 28–36.

Liu, X.X., Xia, Y.Y., Liu, Z.D., et al., 2006. Study of suitability for embankment of highly weathered soft rock subgrade. Rock and Soil Mechanics 27 (6), 903–907.

Manasseh, J., Olufemi, A., 2008. Effect of lime on some geotechnical properties of Igumale shale. Electronic Journal of Geotechnical Engineering 13, 1–11.

Mao, X.S., Zhou, L.G., Ma, B., et al., 2012. Research on improvement technology of filling subgrade with highly-weathered phyllite. China Journal of Highway and Transport 25 (2), 20–26.

Mao, X.S., Li, W.K., Zhang, H.N., et al., 2016. The moisture migration laboratory experiment of strongly weathered phyllite subgrade filling. Science Technology and Engineering 16 (19), 110–115.

Mao, X.S., Zhu, F.J., Huang, Z., et al., 2017. Analysis of influencing factors modified phyllite stuffing CBR value. Journal of Chongqing Jiaotong University: Natural Science Edition 36 (2), 43–48.

Mohamed, Z., Mohamed, K., Cho, G.C., 2007. Uniaxial compressive strength of composite rock material with respect to shale thickness ratio and moisture content. Electronic Journal of Geotechnical Engineering 12 (13), 1–9.

Nie, Z.H., Xiang, Z.M., Hu, Y.F., 2008. Filling characteristics of fully weathered gravel subgrade in passenger dedicated line. Journal of Traffic and Transportation Engineering 8 (6), 49–52.

Nara, Y., Morimoto, K., Hiroyoshi, N., 2012. Influence of relative humidity on fracture toughness of rock: implications for subcritical crack growth. International Journal of Solids and Structures 49 (18), 2471–2481.

Nahazanan, H., Clarke, S., Asadi, A., et al., 2013. Effect of inundation on shear strength characteristics of mudstone backfill. Engineering Geology 158 (3), 48–56.

Pu, C., Meng, L., Li, T., 2017. Study on rupture and energy characteristics of phyllites under triaxial compression. Journal of Engineering Geology 25 (2), 359–366.

Qing, Q.X., Wang, Y.H., Li, G.Y., et al., 2006. Indoor experimental study on express railway embankment with weathered soft rock. Rock and Soil Mechanics 27 (7), 1119–1123.

Qiu, J., Li, D., Li, X., 2017. Dynamic failure of a phyllite with a low degree of metamorphism under impact Brazilian test. International Journal of Rock Mechanics and Mining Sciences 94, 10–17.

Ramamurthy, T., Rao, G.V., Singh, J., 1993. Engineering behaviour of phyllites. Engineering Geology 33 (3), 209–225.

Regmi, A.D., Yoshida, K., Dhital, M.R., et al., 2012. Effect of rock weathering, clay mineralogy and geological structures in the formation of large landslides, a case study from Dumre Besei landslide, Lesser Himalaya Nepal. Landslides 10 (1), 1–13.

Sadisun, I.A., Shimida, H., Ichinose, M., et al., 2002. An experimental study of swelling strain in some argillaceous rocks by means of an improved unconfined swelling test. In: ISRM Regional Symposium (3rd Korean-Japan Joint Symp.) on Rock Engineering Problems and Approaches in Underground Construction, 2002.

Shu, H.M., 2008. The Research on Soft Rock Improvement Soil Experiment and Construction Technology of High-speed Railway (M.Sc. thesis). Central South University, Changsha.

Ulusay, R., Erguler, Z.A., 2012. Needle penetration test: evaluation of its performance and possible uses in predicting strength of weak and soft rocks. Engineering Geology 149 (4), 47–56.

Wang, X.M., Du, Q.W., Cao, Z.Y., 2011. Study on wetting deformation behavior of metamorphic soft rock embankment filler under large-scale compression test. Science Paper Online 6 (5), 363–367.

Xin, Z.L., Geng, F.W., Ling, C., 2014. Test research on influence of water and mineral composition on physical and mechanical properties of phyllite. Applied Mechanics and Materials 496–500, 2398–2401.

Yang, D.S., Bornert, M., Chanchole, S., et al., 2012. Dependence of elastic properties of argillaceous rocks on moisture content investigated with optical full-field strain measurement techniques. International Journal of Rock Mechanics and Mining Sciences 53, 45–55.

Yang, L.Y., Wang, X.M., Zhang, Z., et al., 2010. Deformation characteristics of roadbed filling of soft metamorphic rock before and after soaking in QINLING-BASHAN mountain region. Chinese Journal of Rock Mechanics and Engineering 129 (S2), 3536–3541.

Zhang, N., Liu, L.B., Hou, D.W., et al., 2014a. Geo-mechanical and water vapor absorption characteristics of clay-bearing soft rocks at great depth. International Journal of Mining Science and Technology 24, 811–818.

Zhang, Y.J., Wang, X., Yin, Y.X., et al., 2014b. Experimental study on railway subgrade filling material of phyllite spoil improved with cement. Journal of the China Railway Society 36 (6), 81–86.

Zhao, M.H., Liu, X.M., Su, Y.H., 2005. Experimental studies on engineering properties of red bed material containing slaking rock. Chinese Journal of Geotechnical Engineering 27 (6), 667–671.

Zheng, M.X., Fang, T., Diao, X.L., et al., 2005. Experimental study of feasibility of filled subgrade with weathered soft rock. Rock and Soil Mechanics 26 (S), 54–56.

Zhou, C.Y., Deng, Y.M., Tan, X.S., et al., 2003. Research on the variation regularities of microstructures in the testing of interaction between soft rocks and water. Acta Scientiarum Naturalium Universitatis Sunyatseni 42 (4), 98–102.

Xuesong Mao. Professor, 2013- present, School of Highway, Chang'an University, China. 2012–2013 visiting scholar, Wayne State University, America. 2005–2007 Post-doctoral Fellow, School of Hydraulic Engineering, Xi'an University of Technology. Ph.D., School of Highway, 2004, Chang'an University, Xi'an, China. B.Sc., School of Highway, 1999, Chang'an University, Xi'an, China. Research interest: subgrade and pavement engineering; disaster prevention and mitigation and protection engineering. Presided over more than 20 national, provincial and ministerial level projects. Published over 60 papers and a monograph, many of which were indexed by SCI/EI; invent 40 patents and receive many awards, like second prize of China Highway Association, third prize of Shaanxi Science and Technology.