Review

A Review on Factors Affecting the Resilient Modulus of Subgrade Soils

Mulugeta Damtew Amare[1,2,*], Zoltán Tompai[1]

[1]Department of Geotechnics and Engineering Geology, Faculty of Civil Engineering, Budapest University of Technology and Economics, 1111, Budapest, Hungary
[2] Department of Highway Engineering, Faculty of Civil Engineering, Addis Ababa Science and Technology University, 16417 Addis Ababa, Ethiopia
*e-mail: amaremulugetadamtew@edu.bme.hu

Abstract: The subgrade layer is the lowest pavement layer, which carries the loads transferred from the upper layers. Different researchers have studied the resilient modulus (Mr) of different subgrade soils for the fine-grained and coarse-grained soil types. The layer's resilient response mechanism was found to be different for those fine and coarse materials, and it is vital for improving the pavement performance and life constructed over it. The different parameters related to the soil that can affect the resilient modulus include moisture content, stress level, compaction degree, loading frequency, and matric suction characteristics. Due to the variability of the Mr result, a study is needed for each soil type and input parameter. The effects of these parameters on the Mr are reviewed and discussed in this paper. The results show that the water content beyond the optimum level and the increase in deviatoric stress decreased Mr. In contrast, the increase in confining stress, compaction degree, loading frequency, and matric suction was found to improve the Mr. During the wetting and drying of the soil, the Mr was improved in the drying process.

Keywords: Resilient modulus, Subgrade soils, Moisture content, Stress level, Loading frequency, Matric suction

I. INTRODUCTION

Pavement construction involves the construction of layers (subgrade, subbase, base, and surface layer). It needs analysis and design of each layer before the construction starts. Whether the pavement is flexible or rigid, it requires a solid base to securely withstand and transfer the load from the traffic and the layers above it. Subgrade soils are the foundation for the pavement structure. In the traditional method of design, the design parameter for pavements includes the California bearing ratio (CBR, a measure of a material's resistance to standard plunger penetration under controlled density and moisture conditions) and the static modulus (quantify the relationship between a change in stress and the resulting deformation) [1]. The CBR and static modulus values do not incorporate the traffic's dynamic and actual effects. The mechanistic pavement design method uses the mechanical characterization of unbound granular materials. These materials are characterized by a nonlinear

elastoplastic behavior, which in turn is the Mr of the soil.

The Resilient Modulus (Mr) is a measure of subgrade material stiffness. The resilient modulus of the material is an estimate of its elasticity modulus (E) which often is determined based on the hysteresis loops obtained from cyclic triaxial tests. While the elastic modulus is stress divided by strain for a slowly applied load, this ratio is similar to the resilient modules for rapidly applied loads. It measures the stiffness of the subgrade soil or the actual estimate of the modulus of elasticity. The stress-strain behavior of subgrade soils under repeated traffic loading uses the determination of Mr [2]. The soil's resilient modulus, Mr, is calculated as the ratio of the deviator stress, q, to the recoverable axial strain ε_r .(see equation 1).

$$Mr = \frac{q}{\varepsilon_r} \qquad (1)$$

The triaxial test of the soil determines the resilient modulus in the laboratory. The testing procedure uses a cylindrical test specimen, a repetitive axial

cyclic stress of defined magnitude, load length, and cycle duration. A triaxial pressure chamber produces static confining stress when the sample is subjected to this complex cyclic stress. It is a cyclic version of a triaxial compression test, and the cyclic load application simulates the actual loading of traffic more accurately.

Since the subgrade's resilient characteristics affect the pavement's performance and service life, it is necessary to predict the resilient modulus as accurately as possible. It is also essential to study the contributing factors for the variation of the resilient modulus. Moisture content, stress level, compaction degree, loading frequency, and matric suction properties are some of the soil parameters that could affect the resilient modulus [3].

The amount of moisture inside the soil mass affects the structural response of the soil to any set of applied stresses. The stresses that occur on a given pavement are mainly from the traffic and other inter-layer stresses due to the self-weight of the pavement layers. The stress effect of the traffic is mainly a function of its magnitude, direction, and frequency.

Studies have been conducted to characterize Mr for different subgrade soil [1, 2, 4-7] and found different results for different soil types. Consequently, various studies discussed the effect of other parameters like the moisture content [1, 2, 8], matric suction [2, 8-10], confining stress [1, 2, 8, 11, 12], loading frequency, and compaction [1, 2, 8], and the wetting and drying history of the soil [2, 6] on the Mr. These studies try to model the relationship

Researchers made an increasing number of efforts to predict the resilient behavior of subgrade soils for different scenarios [1-8, 11, 13, 14]. The proposed theoretical and experimental techniques add to the understanding of predicting the resilient response of subgrade materials and how that response evolves due to various contributing factors.

Although there is a fair amount of published information about the Mr of unstabilized and stabilized soils, most of the information is localized because of the use of natural soils as a subgrade and varies accordingly. The variation of the Mr concerning different soil state and stress state parameters initiates the author to review, discuss and summarize the behavior of soil's Mr concerning these parameters.

This paper summarizes factors that affect the resilient properties of subgrade soils. Moisture content, matric suction, confining and deviatoric stress, soil type, load frequency, and compaction degree, as well as the soil's drying and wetting history, are all parameters taken into consideration in this study. This paper looks into the elements that influence the Mr of subgrade soil by reviewing published research. The investigation is limited to the parameters that influence the Mr characteristic of subgrade soil for pavement foundation or subgrade purposes.

II. MATERIALS AND METHODS

Owing to the objective of this study, the data for analyzing the effect of the parameters on the Mr was

Table 1. Summary of studies regarding the factors and number of soil types

| Author's name | Parameters considered on each paper | | | | | | | No of the soil types tested |
	MC	Matric suction	Compaction level	Stress level	Loading frequency	Soil type	Drying and wetting	
X. Liu et al. [1]	+	+	+	+	+	+		6
X. Chu [2]	+	+	+	+	+	+	+	–
A. S. El-Ashwah et al. [4]	+			+		+		10
Y. Yao et al. [5]	+	+			+	+		1
K. Naji [6]	+					+	+	7
Y. J. Cui [7]						+		9
J. Zhang et al. [8]	+	+		+	+			22
C. E. Cary et al. [9]	+	+						2
H. Park et al. [10]		+		+				4
S. Jayakody et al. [11]	+		+	+				1

between these contributing factors and the Mr.

reviewed from published studies (**Table 1 and 2**).

Table 2. *Summary of studies regarding the factors and number of soil types*

Author's name	MC	Matric suction	Compaction level	Stress level	Loading frequency	Soil type	Drying and wetting	No of the soil types tested
N. Su et al. [12]	+			+	+			>6
J. H. Zhang et al. [13]		+		+				–
J. M. Rasul et al. [14]							+	3
X. R. Wu et al. [15]	+							5
R. Ji et al. [16]	+			+				6
F. Salour et al. [17]	+	+						2
X. R Wu et al. [18]	+		+					1
F. Salour et al. [19]	+	+		+				2
F. Achampong et al. [20]	+			+		+		2
A. Rahim et al. [21]				+		+		12
C. N. Khoury et al. [22]	+	+						>2

Among the 123 downloaded relevant and recent papers, 21 studies and two manuals were found close to the objective of this study and selected as a data source. The papers have much data related to the objective of this article. The papers are selected on a basis such that they contain more soil types and parameters concerning the Mr. This study summarizes the works done on more than 103 subgrade soils from different sources and a total of more than 1300 samples. The summary in Table 1 shows the factors considered for the analysis and the number of soils considered in each selected study.

The data for analysis were taken from the published papers, and values that were not found in tabular form were extracted from the figures using GetData Graph Digitizer software. The data collected using this software has 97% accuracy. The data and graphs chosen for each parameter considered in the study are carefully taken from the selected papers to represent the trend of the curves demonstrating the same parameter.

Table 3 presents the summary of the published works interms of the location of the soil samples , the soil classification, and the testing method employed by the respective authors. The AASHTOT307-99 and NCHRP 1-28A (2004) are widely used by the researchers. The soil classification manuals used in the study are mainly AASHTO [23] and USCS [24].

Data extracted from each paper were drawn into a scale for discussion and proving the scientific theories. The researchers utilized different techniques to determine the Mr values. Most of them employ the laboratory determination of Mr using the triaxial loading machine and plate load test for the field testing.

III. Results and Discussion

Though the resilient modulus is the fundamental characteristic parameter, some factors influence its value. Those parameters that can change the subgrade resilient response and studied here are water content, matric suction, confining stress, soil type, load frequency, compaction degree, and soil drying and wetting history [1, 2, 4-8, 11, 14].

1. Moisture content

Due to seasonal environmental variations, the moisture content of unbound pavement layers continuously changes. Different studies stated the impact of this parameter on the resilient response of subgrade soils. For a naturally dried inorganic clay (CL) soil subjected to varying levels of moisture content (MC), the Mr tested and checked for MC levels of -2% of OMC, OMC, and +2% of OMC of the soil [1]. **Fig. 1/a** shows that by keeping the compaction degree to 96% and 1Hz frequency, the variation of the MC affects the soil's resilient response. The dynamic Mr increases with an increase in MC until the OMC level, and afterward, it decreases with an increase in MC [2, 6, 12]. The resilient modulus result of seven different soil samples also decreases with increasing the moisture contents and an increase with decreasing the moisture contents [6].

Table 3. *Summary of studies regarding the location, soil classification , and testing method*

Author's name	Location	Classification	No of the soil types tested
X. Liu et al. [1]	Tianjin, Shijiazhuang, Cangzhou, Xuanhua, Mohe, Nanjing	CL, SM, ML	AASHTOT307-99 (2012) Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, D. C. [25]
K. Naji [6]	Oklahoma and the State of Pennsylvania	Cl, SC, CH, SM	AASHTOT307-99 (2012) Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, D. C. [25]
C. E. Cary et al. [9]	Phoenix Valley, Arizona	A-1-a, A-4	NCHRP 1-28A (2004) protocol "Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design" [26]
R. Ji et al. [16]	Indiana	A-4, A-6, A-7-6	AASHTOT307-99 (2012) Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, D. C. [25]
F. Salour et al. [17]	Northern and Southern Sweden	Two different silty sand subgrade materials (SM)	NCHRP 1-28A (2004) protocol "Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design"
F. Salour et al. [19]	Northern and Southern Sweden	Two different silty sand subgrade materials (SM)	NCHRP 1-28A (2004) protocol "Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design"
F. Achampong [20]		Two blended materials of low and high plasticity clay (CL and CH Soils)	An SBEL HX-100 Triaxial Cell/604 Servo system was used to perform the Mr testing. The AASHTO T-294 (1993) procedure for cohesive soils was followed in performing the Mr tests
A. Rahim et al. [21]	Mississippi (project)	A-4, A-6, A-7, A-2-4, A-2-6, A-3, and A-1-a	A Laboratory MR test, in accordance with the AASHTO TP46 protocol (1994), [27]
C. N. Khoury et al. [22]	Manufactured soil that consists of fine sand (48%), silt (46%), and clay (6%).		AASHTOT307-99 (2012) Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, D. C. [25]

The subgrade soil's resilient response will be low with increasing the MC above the OMC level [15, 16]. This variation becomes very large at lower moisture content levels [17]. For example, when the MC increases from -2% OMC to OMC level, the dynamic resilient modulus increases by an interval of 9% to 20%. However, it decreases by an interval of 24% to 30% for an increment of MC level from OMC to +2%OMC [1]. This happens because the MC that is higher than the OMC creates pore pressure and makes the moisture surround the soil
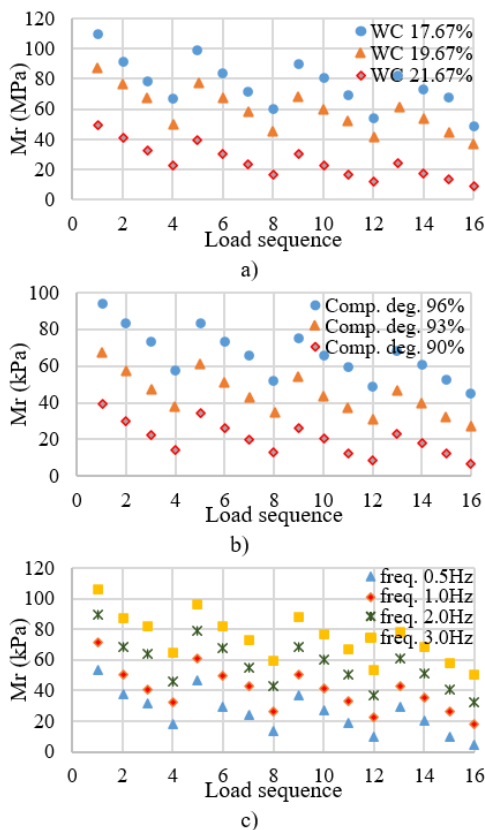
Figure 1. Measured Mr at different a) water content, b) compaction degree, and c) loading frequency [1]

particle surface and causes the soil to lose the cohesive behavior (binding force between soil particles) [19].

Excess moisture in the pavement foundation decreases the subgrade bearing capacity and leads to pavement deterioration [2]. The moisture added will cause a lubrication effect on the soil [1]. Setting the MC level to the optimum value helps the soil to have an improved resilient response; hence it has better cohesion and shear resistance. A study by Wu & Zhu [18] also indicates that the Mr for a loess low liquid limit silt soil shows a variation while the water content changes. The Mr increases by 12.9% when the water content increases from 10.75% to 13.09%

[18]. A study on silty sand subgrade soil of 42.2% and 27.4% fines for change in the degree of saturation from 30% to OMC level results in 51% and 48% reduction to the resilient modulus, respectively [19].

In the review by Chu [2], the moisture content variation within the subgrade soil arises from factors like precipitation, capillary action, flooding, and groundwater table variation. This moisture inside the soil induces positive pore water pressure and reduces the soil's load-carrying capacity, directly related to the Mr of the soil. Though the study is on recycled aggregates [11], the same pattern in the sample's resilient modulus occurs while increasing the degree of saturation. Increased moisture content, particularly at high saturation levels, has been demonstrated to result in a significant decrease in resilient modulus and Poisson's ratio [3].

2. Load frequency and compaction degree

The loading frequency, which is related to the vehicle speed, increases with the resilient modulus [1, 11]. **Fig. 1/c** shows an increase in load frequency (at 19.67% WC and 96% compaction level) from 0.5 Hz to 1.0 Hz and 1.0 Hz to 3 Hz improves the resilient modulus by 14%. The frequency dependency of the subgrade soil's resilient modulus is high at low-stress levels than at high-stress levels [1]. The Mr increases by a small amount at higher stress levels due to the soil's density at these stress levels. A study by Wu & Zhu [15] also shows that the five types of sandy silt soils subjected to varied compaction levels show varied levels of resilient modulus at a given moisture content level. For example, for sandy silt soil with an OMC of 9.3%, the Mr increases by 30.5% when the compaction level increases by 50% [15].

As shown in **Fig. 1/b**, for 19.67% WC and 1Hz load frequency, Mr increases by 26% and 24% when compaction degree increases from 90% to 93% and 93% to 96%, respectively. The level of compaction affects the percentage of voids in the soil so that the higher degree of compaction leads to a lower volume of voids, which has a positive impact on the resilient response of the subgrade soil. The decrease in the volume of voids allows the soil to occupy the space and become more denser and this mechanism with increasing the unit weight of the soil, it also increases the Mr.

3. Matric suction

An increase in matric suction results in a decrease in recoverable strain, which then improves resilient modulus. This parameter affects the soils' resilient property and the sensitivity of the resilient modulus to the bulk and octahedral shear stresses [18].

As pavement subgrade soils are exposed to varying levels of moisture due to the seasonal

environmental variations, the stress developed in the layer is also affected. The stress which dominantly becomes pore pressure at higher degrees of saturation results in lower matric suction, and this is effect is high for fine grained soils [19]. Matric suction has been considered a vital stress variable in investigating the effects of moisture content on the mechanical behavior of unsaturated soils. It mainly consists of two components; osmotic and matric suctions [2]. The matric suction effect is more significant for unsaturated subgrade soils, and experiments show that the Mr is more related to this matric suction than the total suction [2]. Regarding the unsaturated state of the soil, matric suction has been a crucial stress variable in pavement structures with soil mechanics development. Due to the non-linearity of stress-strain parameters at higher matric suction levels, the variation of Mr is significant [17]. As per the study by Farhad et al. [19], the increase in the moisture content of soil materials corresponds to a decrease in the matric suction. It results in a significant reduction in the resilient modulus. **Fig. 2** presents the variation of Mr when the matric suction is changing, and it is seen that the suction increases with the Mr and vice-versa.
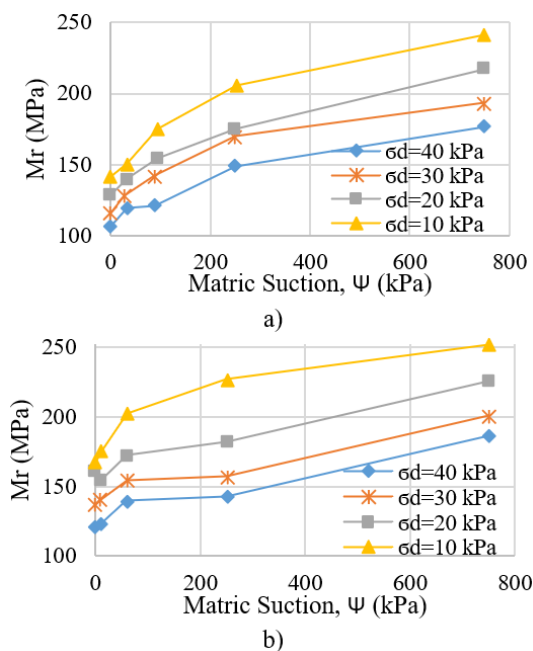
42.2%, the reduction of the matric suction from 444 kPa to 7 kPa results in a 51% reduction in the resilient modulus. For the same soil type of 27.4% fines, the reduction of matric suction from 316 kPa to zero kPa results in a 48% reduction to the resilient modulus [19]. Moisture content differences in fine-grained unbound materials can modify stress by suction, changing material stiffness properties.

4. Confining Stress and Deviator Stress

For a constant MC, compaction degree, and frequency, the dynamic Mr increases with increasing the confining stress [1]. A study by Jayako et al. [11] shows that the resilient modulus increases with increasing confining stress along the constant principal axis. In other words, the deviatoric stress decreases with improving confining stress. Achampong, Usmen, & Kagawa [20] reported similar findings. The Mr increases with an increase in net bulk stress and decreases with increased deviator stress (octahedral shear stress). This effect is significant at higher matric suction values. Salour & Erlingsson [17] added that, at higher matric suction values, the variation of Mr at different stress levels is more significant.

Another study by Yao et al. [5] shows, for a weathered granite subgrade soil (sandy clay of a low liquid limit clay), the Mr significantly decreases with increasing the deviator stress at each compaction degree level. **Fig. 3** presents the result obtained for the variation of Mr concerning the deviatoric stress and cell pressure. It shows that the confining stress positively affects the Mr, while the deviatoric stress has a negative effect.
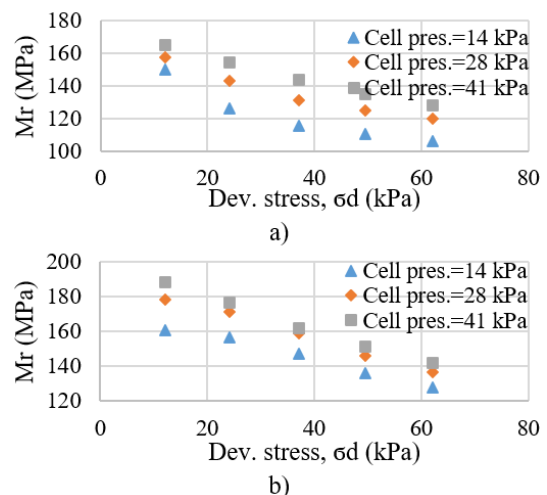

Figure 2. Matric Suction (Ψ) vs. Resilient Modulus (Mr) at 120 kPa Minimum Bulk Stress: a) 95% Compaction, b) 100% Compaction [5]

The resilient modulus increases with increasing matric suction at a certain compaction level [5, 17]. Yao et al. [5] report that, at a compaction level of 85% and deviator stress of 10 kPa, the resilient modulus increases from 107 MPa to 175 MPa when the matric suction increases from 31 kPa to 951 kPa. This result is uniform at each compaction and deviator stress level. For a silty sand subgrade soil of

Figure 3. The effect of cell pressure and deviatoric stress a) for fine-grained soil, b) for coarse-grained soil [21]

Salour et al. [19] reported that resilient modulus increases with bulk stress. It decreases with the

increase in octahedral stress (directly proportional to the deviatoric stress). It is presented that, at 120% OMC and 30 KPa minimum bulk pressure, as the deviator stress increases from 10 kPa to 40 kPa by intervals of 10kPa, the resilient modulus decreases by 20.7%, 13.0%, 19.7%, and 5.4% under a degree of compactions of 100%, 95%, 90%, and 85%, respectively [5]. Similarly, for the same soil type and condition at minimum bulk stress of 120 kPa, the resilient modulus decreases by 30.8%, 30.6%, 19.0%, and 11.8%. Rahim & George [21] also backed this idea in the study focused on the correlation between Mr and stress conditions for fine-grained and coarse-grained soil.

Densification of the soil material improves Mr and decreases the elastic strain of the soil. Similarly, the increase in the confining stress, since it confines the soil in all directions, is an addition to its shear strength. The increase in the deviator stress enhances the shear failure of the soil mass along the weak plane. Therefore, the confining stress increases the soil mass's resilient response while the deviator stress lowers this response mechanism [10].

5. Soil type and classification

Different soil types exhibit different characteristics as well as different response mechanisms. The resilient response mechanism of different soil samples is tested and found to be different [15]. Naji [6] shows different resilient modulus values for seven soil classes from two different regions, Oklahoma and Pennsylvania; namely, Kingfisher (CL), Binger (SC), Burleson (CH), Renfrow (CL), Stephensville (SM), Alloway Clay (CH), and Made Land (CL). Though the pattern of increase and decrease is similar for most soils, the degree of increase or decrease in Mr values is a function of soil type [6]. Farhad [19] also suggests that the resilient response is different even for the same soil type with different fine content. For example, the change in matric suction for two silty sand soils with 42.2% and 27.4% fine passing No.200 is different due to the moisture content variation from 30% to the OMC [19]. As a result, Mr also varies accordingly. Soils with less fine content tend to have less matric suction and a higher resilient modulus.

Another study by Rasul et al. [14] shows different Mr values for three different subgrade soil types (A-7-5, A-4, and A-6 soils [25]) found in Kurdistan. It is shown that the three different soils, whether treated or untreated by lime and or cement, the Mr remains different. For example, **Table 4** shows that the three soils subjected to equal level confining stress and deviator stress have different Mr values. The soil with more coarse soil content have the largest Mr value and vice-versa. The response of the finer soil classes to a given cyclic load is weak.

Table 4. *Resilient modulus values for soil A-4, A-6, and A-7-5 at unstabilized and stabilized state [14]*

Soil type	Confining stress (kPa)	Deviator stress (kPa)	Resilient modulus (MPa)	Mr for cement treated 2% (MPa)
A-4	41.4	12.4	117	131
	27.6	37.3	150	185
	12.4	62.0	165	222
A-6	41.4	12.4	96	139
	27.6	37.3	105	171
	12.4	62.0	100	196
A-7-5	41.4	12.4	74	76
	27.6	37.3	69	98
	12.4	62.0	57	117

The magnitude of the effect of the parameters like stress state, moisture content, and matric suction towards the materials' resilient response differs from the soil classification. Unsaturated subgrade soils with high fine content have the highest resilient response, or the magnitude of change of Mr for those soil types is much more significant than for saturated and less fine content soils [17]. The state of the soil, either drained or undrained, is also a significant contributing factor [9]. This factor becomes more substantial when the degree of saturation becomes higher.

Achampong et al. [20] reported that mineralogical composition has a marked effect on the Mr of cohesive soils. They found that soils with higher kaolinite clay minerals have higher Mr values than the soils with high montmorillonite clay minerals.

An indirect approach was employed by Rahim & George [21] and uses the ratio of deviator stress to confining stress for the fine-grained soils and the ratio of bulk stress to deviator stress for the coarse-grained soil samples. It is stated that the two parameters in the first ratio best capture the effect for the fine-grained soils, and the latter is found to best describe the effect for coarse-grained soils. The Mr

increases with an increase in the ratio of deviator stress to confining pressure, and it has a reverse correlation for the ratio of coarse grain soil parameters. This pattern is due to fine- and coarse-grained soils' stress softening and hardening characteristics [21].

6. Drying and wetting history of the soil

Seasonal variation is one cause of subgrade soils' drying and wetting process. The effect becomes higher in regions where freeze and thaw actions are dominant. A study by Ji et al. [16] compared the resilient property of subgrade soils at different seasons of the year. The results obtained from this study show that the Mr measured by FWD in April, July, October, and December are 180 kPa, 190 kPa, 197 kPa, and 212 kPa, respectively. In other words, Mr increases as we approach the cold season (from October to January), and it will continue increasing until the soil reaches its OMC level. After reaching the OMC level and while the ice melts gradually (on March, April, and May), the Mr tends to decrease. The increase and decrease of the soil's moisture level due to the variation of the seasons in a given period causes the variation and lowering of the soil's cohesive and shear behavior. Moreover, it results in a decrease in the resilient modulus.

Table 5 shows that the drying and wetting process has different effects on the Mr. The drying process, which is the loss of moisture from the soil mass, shows the improvement of Mr value, and later, it decreases. At the same time, the soil is subjected to the wetting process. The latter pattern is more consistently shown in the characteristic of Mr in the process of drying and wetting. The primary drying and primary wetting are the states or complete cycles where the soil was subjected initially.

Table 5. *Effect of drying and wetting at confining stress of 41 kPa and deviatoric stress of 28 kPa [22]*

Condition	Suction (kPa)	W (%)	R^2	Mr (kPa)
Primary drying	8	17.2	0.90	28.1
	25	13.1	0.94	43.8
	50	9.6	0.92	71.6
	75	6.1	0.95	96.9
	100	4.3	0.96	114.1
Primary wetting	75	4.8	0.96	110.3
	50	5.9	0.94	99.5
	25	9.0	0.95	82.8
Secondary drying	25	11.0	0.95	71.2
	50	7.9	0.95	91.6
	75	5.7	0.97	110.3
	100	4.4	0.95	125.2
Secondary wetting	75	4.7	0.94	117.0
	50	5.7	0.94	100.7
	25	7.6	0.96	84.5

In contrast, the secondary drying and secondary wetting states are the second cycles that follow the first complete cycle. Khoury et al. [22] added that the hardening effect due to cyclic suction and the potential lubricant effect of the water content (at the same suction) is assumed to be the dominant cause for higher Mr on wetting relative to drying.

A study by Rasul et al. [14] on three different lime and cement stabilized subgrade soils to a different degree shows that the wetting and drying history of the soil affects its resilient response. The wetting and drying condition of the soil modeled in the lab uses entirely soaking the subgrade soil for 5 hrs at room temperature and letting it dry in an oven for around two days. For 25 cycles, the soil sample report shows that the soil becomes loess, and the volume changes. For example, the resilient modulus value for stabilized sandy clay soil (A-7-5) decreases up to 31% after the soil gets into the soaking and drying process beyond its optimum level. This is because the soil collapse as the wetting and drying condition continues. The study [14]suggests the same scenario of Mr happens for three soil samples (A-7-5, A-4, and A-6 soils [28]) in both treated and untreated conditions.

Another related factor to the soil's wetting and drying condition is climatic changes, which will lead to the build-up and breakdown of soil particles, and the aggregate stability inside the soil becomes negatively affected. On the review by Chu [2], the resilient modulus will increase slightly for lime-treated soils during the wetting and drying process, and the resilient modulus decreases for unstabilized soils. For soils compacted at their OMC level, the Mr decreases up to several times [2, 6].

IV. CONCLUSIONS

The parameters that affect the resilient modulus studied here are the stress state, matric suction, moisture content, soil type, wetting and drying history, and degree of compaction and loading frequency. Specifically, the review can be summarized as follows:

- Mr increases with increasing moisture content and matric suction. It keeps increasing up to the optimum moisture content level, and beyond the optimum point, the Mr will decrease.
- Mr increases with increased confining and net bulk stress and decreases with increased deviator stress (octahedral shear stress).
- Soils with more fine content have Mr values higher than the soil types with less fine content.
- Mr increases with the increase in loading frequency and compaction level. The

change in Mr becomes high at low-stress levels than high-stress levels.

- The seasonal temperature and climate fluctuation alter the Mr of subgrade soils. Mr increases in the drying process of the soil and vice versa.

ACKNOWLEDGEMENT

AUTHOR CONTRIBUTIONS

M. D. Amare: Writing, Review and editing.

Z. Tompai: Writing, Review and editing.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID

M. D. Amare https://orcid.org/0000-0002-5525-7650

Z. Tompai https://orcid.org/0000-0002-8794-7664

REFERENCES

[1] X. Liu, X. Zhang, H. Wang, B. Jiang, Laboratory testing and analysis of dynamic and static resilient modulus of subgrade soil under various influencing factors, Construction and Building Materials 195 (2019) pp. 178–186. https://doi.org/10.1016/j.conbuildmat.2018.11.061

[2] X. Chu, A Review on the Resilient Response of Unsaturated Subgrade Soils, Advances in Civil Engineering (2020), 7367484 https://doi.org/10.1155/2020/7367484

[3] F. Lekarp, U. Isacsson, and A. Dawson, "State of the Art. I: Resilient Response of Unbound Aggregates," Journal of Transportation Engineering-asce - J TRANSP ENG-ASCE 126 (1) (2000) https://doi.org/10.1061/(ASCE)0733-947X(2000)126:1(66)

[4] A. S. El-Ashwah, A. M. Awed, S. M. El-Badawy, and A. R. Gabr, "A new approach for developing resilient modulus master surface to characterize granular pavement materials and subgrade soils," Construction and Building Materials 94 (2019) pp. 372-385.

[5] Y. Yao, J. Zheng, J. Zhang, J. Peng, and J. Li, "Model for predicting resilient modulus of unsaturated subgrade soils in south China," KSCE Journal of Civil Engineering 22 (6) (2018) pp. 2089-2098.

[6] K. Naji, "Resilient modulus–moisture content relationships for pavement engineering applications," Int. J. Pavement Eng. 19 (7) (2018) pp. 651-660.

[7] Y. J. Cui, "Mechanical behaviour of coarse grains/fines mixture under monotonic and cyclic loadings," Transportation Geotechnics, Review 17 (2018) pp. 91-97. https://doi.org/10.1016/j.trgeo.2018.09.016

[8] J. Zhang, J. Peng, L. Zeng, J. Li, and F. Li, "Rapid estimation of resilient modulus of subgrade soils using performance-related soil properties," Int. J. Pavement Eng. (2019) pp. 1-8.

[9] C. E. Cary and C. E. Zapata, "Resilient modulus for unsaturated unbound materials," Road Materials and Pavement Design 12 (3) (2011) pp. 615-638.

[10] H. Park, G. Kweon, and S. R. Lee, "Prediction of resilient modulus of granular subgrade soils and subbase materials using artificial neural network," Road Materials and Pavement Design 10 (3) (2009) pp. 647-665.

[11] S. Jayakody, C. Gallage, and J. Ramanujam, "Performance characteristics of recycled concrete aggregate as an unbound pavement material," Heliyon, Review 5 (9) (2019), Art no. e02494 https://doi.org/10.1016/j.heliyon.2019.e02494

[12] N. Su, F. Xiao, J. Wang, and S. Amirkhanian, "Characterizations of base and subbase layers for Mechanistic-Empirical Pavement Design," Construction and Building Materials, Review 152 (2017) pp. 731-745. https://doi.org/10.1016/j.conbuildmat.2017.07.060

[13] J. H. Zhang, J. H. Peng, and J. L. Zheng, "Progress and Prospect of the Prediction Model of the Resilient Modulus of Subgrade Soils," Zhongguo Gonglu Xuebao/China Journal of Highway and Transport, Review 33 (1) (2020) pp. 1-13. https://doi.org/10.19721/j.cnki.1001-7372.2020.01.001

[14] J. M. Rasul, G. S. Ghataora, and M. P. Burrow, "The effect of wetting and drying on the performance of stabilized subgrade soils," Transportation Geotechnics 14 (2018) pp. 1-7.

[15] X. R. Wu and L. L. Zhu, "Analysis of the influence of water content on shanxi loess CBR and rebound module," in H. Abbas and T. K.

Hwee Eds., Advanced Materials Research. Durnten-Zurich: Trans Tech Publications Ltd 919-921 (4) (2014), pp. 820-823.

[16] R. Ji, N. Siddiki, T. Nantung, and D. Kim, "Evaluation of resilient modulus of subgrade and base materials in Indiana and its implementation in MEPDG," The Scientific World Journal 2014 (2014).

[17] F. Salour and S. Erlingsson, "Resilient modulus modelling of unsaturated subgrade soils: laboratory investigation of silty sand subgrade," Road Materials and Pavement Design 16 (3) (2015) pp. 553-568.

[18] X. R. Wu and L. L. Zhu, "Study on the Relations of Strength control indicators of road subgrade in shanxi loess region," in H. Abbas and T. K. Hwee Eds., Advanced Materials Research. Durnten-Zurich: Trans Tech Publications Ltd 919-921 (2014) pp. 1160-1163.

[19] F. Salour, S. Erlingsson, and C. E. Zapata, "Modelling resilient modulus seasonal variation of silty sand subgrade soils with matric suction control," Can. Geotech. J. 51 (12) (2014) pp. 1413-1422.

[20] F. Achampong, M. Usmen, and T. Kagawa. Evaluation of resilient modulus for lime- and cement-stabilized synthetic cohesive soils, Transportation Research Record (1997) pp. 70-75.

[21] A. Rahim and K. George, "Models to estimate subgrade resilient modulus for pavement design," Int. J. Pavement Eng. 6 (2) (2005) pp. 89-96.

[22] C. N. Khoury, N. N. Khoury, and G. A. Miller. Effect of cyclic suction history (hydraulic hysteresis) on resilient modulus of unsaturated fine-grained soil, Transportation Research Record (2011) pp. 68-75.

[23] AASHTO, "AASHTO M 145 (1991), AASHTO Standard Specification for Classification of Soils and Soil–Aggregate Mixtures for Highway Construction Purposes," 1991.

[24] A. C. D.-o. Soil and Rock, Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) 1. ASTM international, 2017.

[25] AASHTO, "AASHTO T 307-99 (2007), AASHTO Standard method of test for determining the resilient modulus of soils and aggregate materials, Washington D.C.," 2009.

[26] T. R. Board, E. National Academies of Sciences, and Medicine, Laboratory Determination of Resilient Modulus for Flexible Pavement Design. Washington, DC: The National Academies Press (in English), 2004.

[27] AASHTO, "AASHTO T 274 (1994), AASHTO Standard Method of Test for Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils - SHRP Protocol P46," 1994.

[28] ASTM, "ASTM D 559-96, (2003), Standard test method for wetting and drying of compacted mixture, ASTM International, Pennsylvania, USA."