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Evaluation of Conventional and Sustainable Modifiers to Improve the Stiffness Behavior of Weak Sub-Grade Soil

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Abstract: The paper focuses on the improvement of the clayey soil (A-6) with the locally available and cheap modifiers, in terms of stiffness behavior of the weak subgrade soil for flexible pavement. The modifiers used include lime (hydrated), marble waste and sand. The soil specimens underwent triaxial testing and Clegg impact testing. Triaxial testing involved the assessment of the resilient modulus (M_R) and impact testing using the Clegg Impact Hammer. According to the study, lime proved to be the most influencing modifier as it improves the stiffness of the weak soil better than other modifiers. A quite accurate statistical relationship between the M_R and the variables (including Clegg Impact) involved in the testing procedure has been established

Keywords: flexible pavements; resilient modulus (M_R); subgrade; modifiers; triaxial test

1. Introduction

Environmental sustainability is defined as the use of recycled resources to meet contemporary needs without decrementing the demands of the succeeding generation, and it has become an emerging concept of millennium development targets [1]. Therefore, researchers are striving to explore modern techniques to ensure the sustainability of the environment. Waste production and depletion of resources have become a growing concern globally. Road networks and transportation play a vital role in achieving the sustainability of the environment. Transportation is the backbone of the economy of a country, and its importance is much greater in developing countries. Thus, use of waste materials for improving the strength and performance of road pavements has been found to be a pertinent way of achieving economic efficiency for a sustainable transportation infrastructure.

During the past few years, highway engineers are facing common problems, i.e., rutting and cracking, which lead to the premature failure of flexible pavements. Pavement and subgrade are the main constructive elements, on which the strength and operational life of the highway depends [2]. A typical flexible pavement is composed of layers of several materials. The load is shifted to the subgrade layer through this multilayer system. This subgrade layer acts as a foundation for the pavement [3]. The ability of the pavement to accommodate the compressive stresses is termed as strength of subgrade soil [4]. If weak subgrade soil is encountered, soil properties can be improved by using different stabilizing techniques, keeping in view the economy of the highway projects [5]. Poor subgrade containing expansive soil has greater tendency of swelling and shrinking when it comes in contact with water. This behavior is supposed to occur because of rich montmorillonite minerals of clay. This behavior of expansive soils can be minimized by using some chemical or cementitious additives [6]. Improvement of sandy soils using soil injection technology by expandable polyurethane resin resulted in less settlement and ultimate stabilization of the soil [7].

The world is witnessing latest trends and contemporary techniques in the form of utilization of waste material to enhance the engineering characteristics of the poor soils. The main factor behind this trend is the production of huge quantities of wastes like marble, lime, and many other industrial and agricultural wastes. These wastes create the hazardous environmental concerns and deplete the landfill spaces. To resolve such issues, one of the best workable solutions is to use these waste materials on construction sites, mainly highway projects [8]. These waste materials can be utilized as a good economical option in civil engineering projects to stabilize the weak soil [9]. Solid waste materials having alumino-silicate content enhanced the strength and mechanical properties of soft soils significantly [10]. Soil stabilization by using compound materials can serve as a better alternative from an economic point of view [11]. Liquid limits, dry densities, swelling pressures and swell potential decreased significantly by the addition of waste tire rubber and cement [12]. Soil stabilization using cement is not generally preferred due to its excessive cost and environmental concerns. Marble dust was suggested as a good choice to improve the pavement subgrade soil [13]. Rice Husk Ash, Sugarcane Bagasse Ash and Cow Dung Ash were used for stabilization of subgrade for rural roads [14,15]. Use of nano-materials to stabilize the weak soil was studied, and nano silica yielded more durability and strength as compared to lime stabilized soil [16]. Soil stabilization is beneficial to improve weak soil in an economic way. To stabilize the weak soil, most waste materials act as stabilizing agents that give better results [17]. Stress was laid upon the usage of electronic waste for stabilization of weak soil owing to the large production of E-waste per annum in the region [18].

As the research has made prominent advancements in recent years, more favorable methods have been introduced to assess the stiffness of subgrade soil in pavements. California Bearing Ratio (CBR) has been proven to be a less effective technique, so the attention is transferred to use M_R because it triggers with insitu conditions [19]. A number of researchers have developed models for resilient modulus in relation to soil properties and different stabilization techniques [20]. Researchers also focused on the development of correlation between the resilient modulus and thermal conductivity of construction and demolished material for geothermal pavement applications. Adaptive neuro-fuzzy inference system (ANFIS) model performed well with $R^2 = 0.99$ [21]. Estimation of resilient modulus has been modeled as routine soil properties using long term pavement performance and spatial variability of soil properties. Three machine learning methods (i.e., gradient boosting regression (GBR), adaptive neuro-fuzzy inference system (ANFIS) and artificial neural network (ANN)) performed well with R^2 value more than 0.9 [22]. An experimental study focused on the utilization of plastic waste in pavement construction and found the impact on thermal conductivity, resilient modulus and strength properties [23]. Artificial neural network and genetic algorithms were used for prediction of resilient modulus of subgrade in relation with soil index properties [24]. In the past researches, Clegg Hammer test has been used to supplement the results of M_R. Relationship between CBR and M_R has been witnessed earlier, but only few works have addressed the correlation of CIV and M_R. Multiple researches have concluded that CBR is no more helpful to assess the actual dynamic loading on pavement [25,26]. Researchers contributed in developing an excellent methodology for predicting and evaluating M_R values of subgrade soils to use in pavement design procedures, conducting field and laboratory testing methods [27,28]. Research was conducted on different soils being used in Florida State to determine the Correction Factors (CFs) for equivalent laboratory Resilient Modulus giving the appropriate moduli of unbound granular layer to assist the flexible pavement design based on Mechanistic Empirical Pavement Design Guide (MEPDG) [29]. Suitability of application of M_R testing protocol NCHRP 1-28A for unsaturated soils was also assessed [30]. As the calculation of M_R in laboratory is complex and time-consuming process, many researchers have studied the relationship between CBR and soil index properties to obtain M_R. In present research, results of impact value and modified proctor test have been correlated with M_R by using linear and nonlinear regression techniques.

In this study, a weaker soil (A-6 as per AASHTO soil classification system) was selected as A-6 soil is encountered at highway projects in many parts of the country (Pakistan). Locally available cheap modifiers, i.e., marble waste, sand and lime, are used in six different percentages to improve the stiffness of weak soil. The resilient modulus (M_R) and Clegg Impact Values (CIV) are determined by performing triaxial and Clegg Impact Hammer tests. Values of resilient modulus were calculated and regression models were successfully developed for typical A-6 soils. Quite notable correlations were found between the resilient modulus and outcomes of other experiments.

This research is focused on the improvement of AASHTO soil group A-6 for pavement subgrade. The research aims to study the effect of different percentages of conventional modifiers such as sand, marble waste and lime on stiffness of weak subgrade soil (A-6) to develop M_R database for pavement design applications.

As resilient modulus testing is a tough and time-consuming method laid down to estimate the behavior of subgrade soils against different stress conditions to replicate the vehicular traffic loading, the following main objectives are targeted to improve M_R followed by its prediction model.

- To study the effect of optimum moisture content, maximum dry density, and different percentages of conventional modifiers on M_R and Clegg Impact Value.
- To establish correlation between M_R and Clegg Impact Value
- To develop the regression model between M_R and other variables involved in the study.

2. Materials and Methods

Soil samples collected from the test site, situated at section-I of GT Road, Punjab Pakistan. The investigated soils were selected so that test results can be utilized to find out M_R of subgrade soil. Detailed laboratory tests were conducted based on the standard methods of the American Society for Testing and Materials (ASTM) and American Association of State Highways and Transportation Officials (AASHTO).

Soil index properties including gradation (AASHTO T-87 and T-88), liquid limit (AASHTO T-89), plastic limit (AASHTO T-90), Hydrometer Test (AASHTO T-87) and Specific Gravity of Soil (AASHTO T-100) were determined. The Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) were determined using the modified Proctor test (AASHTO T-180). Sieve analysis is performed on A-6 soil according to the ASTM C136 and AASHTO T-87 and T-88. Three tests were performed for the sieve analysis. The tests performed for the characterization showed that the soil samples collected from the site were pure A-6 soils as shown in Figure 1. Table 1 shows the results for different soil index properties, i.e., Sieve analysis, Atterberg limits, plasticity index, hydrometer analysis, proctor test and specific gravity, etc.

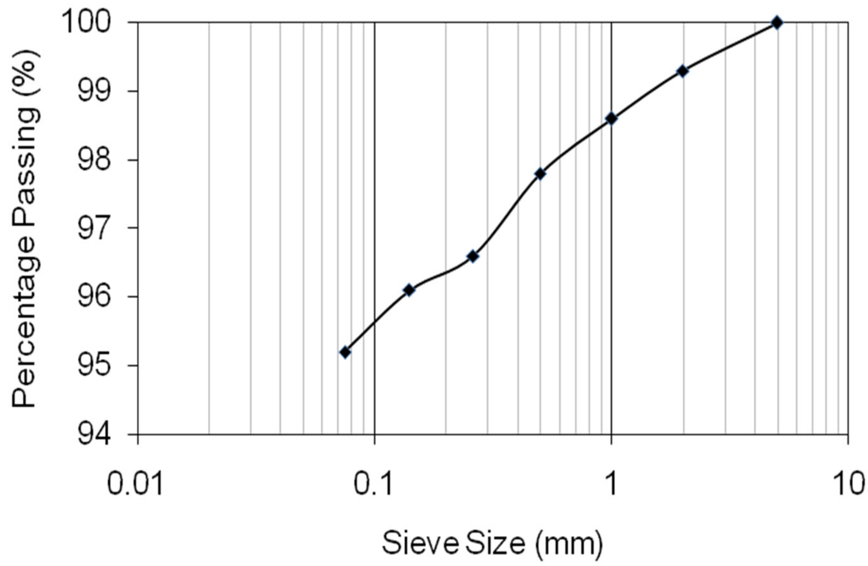

Figure 1. Gradation Curve of A-6 Soil.

Table 1. Soil Index Properties.

Sr. No.	Description	Results
1	Liquid Limit (%)	26
2	Plasticity Index	11
3	Moisture content (%)	9.4
4	Maximum Dry density (g/cc)	2.13
5	Specific gravity	2.50

2.1. Assessment of Soil Stiffness

Assessment of stiffness property has been determined by resilient modulus and Clegg Impact Value, which were obtained using triaxial (NU-14) shown in Figure 2 and impact hammer tests, respectively. Specimen preparation for triaxial compression tests was conducted as per AASHTO T307 standard test method to estimate the resilient modulus of soil. Samples were prepared in special mold (101.6 mm diameter and 203.2 mm height). Samples were compacted by using hydraulic jack system in five layers on 100% compaction. Figure 3 shows different soil samples prepared for the assessment of soil stiffness. For sample preparation, type-2 soil was used categorized by the AASHTO T307. In detail, this standard divides subgrade soils in two types. Soils fall in the category of Type 1 if less than 70% passing 2 mm sieve and less than 20% passing the No. 200 sieve (75-µm), with plasticity index of 10 or less. Type1 soils are compacted in a 152.4 mm diameter mold. Any soil not fulfilling the criteria of Type 1 will be considered as Type 2 soils. Type-2 soils are compacted in mold of 71.12 mm/101.6 mm diameter. All soil samples which are used for this research are Type 2 material.

The testing order to estimate the resilient modulus of subgrade soils is shown in Table 2. The cyclic loading is applied a haversine shape form of $(1 - \cos \Phi)/2$. The maximum axial stress is described as the cyclic stress including contact stress, while the contact stress is 10% of the maximum axial stress. A contact stress on the specimen is required to ensure a close contact between the specimen and platens during the whole cyclic process. If a close contact between the loading platens and the specimen is not maintained, it may result in less precise measurement of resilient modulus. The cyclic stress is considered as 90% of the maximum applied axial stress from which the resilient modulus is estimated. The cyclic stress pulse has time lap of 0.1 s with a recess of 0.9 s. During the recess time of 0.9 s, a contact stress is required to ensure the contact between the loading platens and the sample.

Figure 2. Setup of Triaxial test NU-14.

Figure 3. Specimens tested for resilient modulus test.

Table 2. Testing Sequence for Subgrade Materials.

Sequence Number	Confining Pressure, σ_3 (Pa)	Maximum Axial Stress, σd (kPa)	Cyclic Stress, σ_{cd} (kPa)	Contact Stress, σ_d (kPa)	Number of Load Applications
Conditioning	41.37	27.58	24.82	5.51	500–1000
1	41.37	13.79	12.41	6.89	100
2	41.37	27.58	24.82	1.38	100
3	41.37	41.37	37.23	2.75	100
4	41.37	55.16	49.64	4.14	100
5	41.37	68.94	62.05	5.51	100
6	27.58	13.79	12.41	6.89	100
7	27.58	27.58	24.82	2.75	100
8	27.58	41.37	37.23	4.14	100
9	27.58	55.16	49.64	5.51	100
10	27.58	68.94	62.05	6.89	100
11	13.79	13.79	12.41	1.37	100
12	13.79	27.58	24.82	2.75	100
13	13.79	41.37	37.23	4.14	100
14	13.79	55.16	49.64	5.51	100
15	13.79	68.95	62.05	6.89	100

The impact of modifiers was also studied for stiffness property of the subgrade soil. The modifiers included lime (Pulverized), Marble Waste, and Sand, collected from the local industries. Mineral composition of clay, marble, lime and sand are given in Table 3. The different concentration of modifiers was used, as shown in Table 4.

Table 3. Mineral Composition of the Clay (A-6), Lime, Marble and Sand.

Mineral Composition of Clay (A-6)	
Mineral	Percentage
Illite	37%
Kaolinite	12%
Chlorite	5%
Quartz	45%
Hematite	6%
Mineral Composition of Lime	
Mineral	Percentage
Calcite	98.70%
Montmorillonite	-
Quartz	1.30
Dolomite	-
Mineral Composition of Marble	
Mineral	Percentage
Illite	3.2%
Calcite	90.35%
Chlorite	0%
Quartz	0%
Dolomite	2.43%
Ankerite	2.4%
Albite	0.85%
Pyrite	0.08%

Table 3. *Cont.*

Mineral Composition of Sand	
Mineral	Percentage
Calcite	14.21%
Kaolinite	7.89%
Quartz	21.26%
Dolomite	14.58%
Smectite	9.10%
Halite	7.99%

Table 4. Modifiers Percentages.

Lime (%)	Marble Waste (%)	Sand (%)
2	3	3
4	5	6
6	7	9
8	9	12
10	11	15
12	13	18

The findings of the test were then collected from a self-generated result sheet by the computer. The results were then analyzed and reports were prepared. Similar procedure was adopted for Clegg Impact Value determination. The Clegg Impact soil test provides a means for measuring and controlling soil strength and consolidation levels. It is also used to confirm uniform compaction over wide areas of ground, identifying poorly compacted areas and ineffective rolling of materials. The standard test method, using a 10 lbs hammer, is suitable for, but not limited to, evaluating the strength of an unsaturated compacted fill, in particular pavement materials, soils, and soil-aggregates having maximum particle sizes less than 37.5 mm.

In this study, Clegg Impact Hammer was used (according to ASTM D 5874-02) to calculate the impact value of the molds. The molds were prepared in the laboratory in 6 in diameter mold.

2.2. Data Modeling

The statistical analysis was performed during this research as well. Two different types of analysis were performed. The software Minitab developed the correlation between all the variables and resilient modulus. In one analysis, resilient modulus was related to the various factors being involved in the study, i.e., “Filler types”, “% Filler”, “Clegg Impact Value”. “Optimum Moisture Content” and “Maximum Dry Density”. In the second analysis, resilient modulus was related to the Clegg Impact Value. The software “Minitab” and “Statistical analysis tool of Microsoft Excel” were used for this purpose.

$$\begin{gathered} M_R = -3.34 \times 10^7 - 157(\text{F.T.}) + 3.95 \times 10^5(\%\text{F}) + 1.24 \times 10^6(\text{OMC}) \\ +1.6 \times 10^5(\text{MDD}) + 3.64 \times 10^5(\text{CIV}) \end{gathered} \quad (1)$$

where F.T. refers to type of the filler (modifier), %F refers to percentage of filler (modifier) used, OMC refers to optimum moisture content (%), MDD refers to maximum dry density (kN/m^3) and CIV refers to Clegg Impact Value used.

The statistical analysis tool of Microsoft Excel was used to establish the direct relationship between the resilient modulus and Clegg Impact Value. It was a general relationship which can be used for all types of modifiers. The relationship is shown in the Equation (2).

$$M_R = 22.98(\text{CIV})^{1.02} \quad (2)$$

3. Results and Discussion

The liquid limit test was performed by adopting the procedure described in AASHTO T-89; plot shown in Figure 4 represents the liquid limit (26%).

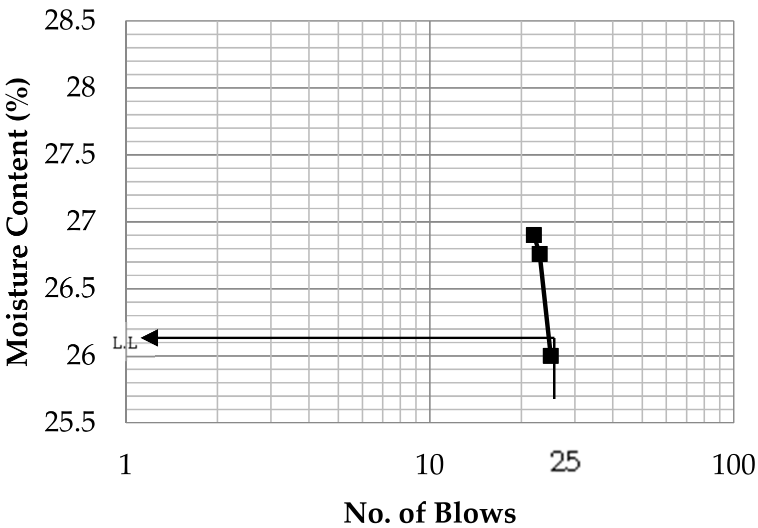

Figure 4. Flow Curve of A-6 Soil.

The plastic limit was calculated on the basis of AASHTO T-90. It was found to be 11%. Table 5 shows the summary of modified proctor tests. OMC shows the same trend for marble waste and sand modifier; as the percentage of modifier increases, OMC tends to decrease. In case of waste lime, increase in modifier percentage causes an increase in OMC, whereas MDD decreases because addition of lime immediately affects the properties of soil by ion exchange of Ca 2+ with monovalent ions and results in decrease in plasticity. The clay particles become electrically attracted to one another (interparticle attraction), causing flocculation and aggregation which results in a modification of soil from a cohesive material to a more granular one. As sand has zero plasticity, particles are large and do not change shape when wet, so increase in sand contents decrease the MDD and OMC [31–35]. MDD in case of Marble waste increases upto a certain level and then decreases afterwards because of gradual formation of cementations compound upto a certain limit [36]. For lime and sand, MDD decreases with increase in percentage of the respective modifier.

Table 5. Summary of Modified Proctor Test.

Lime (%)	Proctor Test		Marble Waste (%)	Proctor Test		Sand (%)	Proctor Test	
	OMC (%)	MDD (g/cc)		OMC (%)	MDD (g/cc)		OMC (%)	MDD (g/cc)
2	9.8	2.09	3	9.3	2.23	3	9.2	2.08
4	10.2	2.06	5	8.9	2.30	6	8.78	2.02
6	10.8	2.02	7	8.75	2.30	9	8.23	1.97
8	11.4	1.96	9	7.9	2.36	12	7.89	1.92
10	12.3	1.92	11	7.6	2.21	15	7.36	1.90
12	12.9	1.90	13	7.2	2.20	18	6.9	1.89

Figure 5 shows the relationship between the optimum moisture content (at which the samples were prepared) and the resilient modulus. The resilient modulus values, i.e., stiffness of the soil tends to increase on increasing the moisture up to a certain level. The further increase in the water content decreases the stiffness of the soil. This trend has been same in case of all the three modifiers. In case of lime, the moisture content increases with the increased percentage of lime whereas for both other modifiers, the moisture decreases as shown in the Figure 5 that is consistent with the previously published study [37]. As far as the resilient modulus is concerned, all the modifiers improved the stiffness of the soil up to a certain level. The optimum moisture contents are 11.4, 7.9 and 7.89% for waste lime, marble waste and sand, respectively.

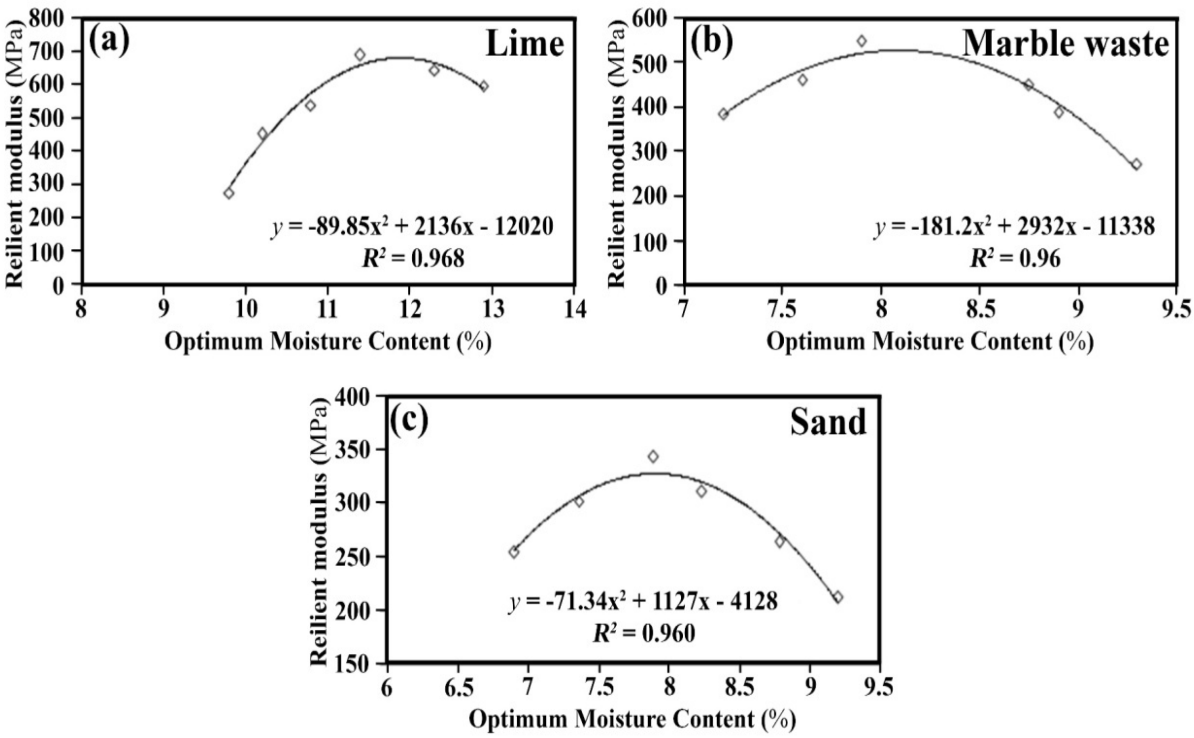

Figure 5. Effect of Optimum Moisture Content on Resilient Modulus. (**a**) lime; (**b**) marble waste; (**c**) sand.

Figure 6 is a depiction of the resilient modulus against the maximum dry density found by the modified compaction test. The maximum dry density tends to decrease with the increasing percentage of modifier, whereas the resilient modulus increases first and decreases afterwards. This is consistent with previous researches [38].

Figure 7 presents the relationship between the percentage of modifiers and resilient modulus. Moreover, Figure 7 describes the influence of all the modifiers on the soil in terms of stiffness. From the Figure 7, it is very clear that the lime improved the soil stiffness most of all, whereas the effect of sand was less than the rest of modifiers. In calcareous material, lime has been studied by Biczysko [39] and Little et al. [40] to increase the development of carbonate cement that chains carbonate particles together and results in a significant shear strength and a notable increase in the stiffness. It can be observed that the optimum percentage for lime, marble waste and sand is 8, 9 and 12%, respectively, where maximum resilient modulus values are achieved.

Figure 8 describes the effect of deviatoric stresses on resilient modulus when confining pressure is kept equal to 41.4, 27.6 and 13.8 kPa for all the modifiers. The relationship follows the ideal trends in case of all the three different confining pressures.

Figure 9 helps to determine the optimum percentage of water to be added to the soil to improve its strength at the optimum percentage of modifiers. In case of lime, the percentage of moisture increases with the increase in percentage of lime, whereas for sand and marble waste, the relation is reverse. OMC for waste lime, marble waste and sand were found 11.4, 7.9, and 7.89%, respectively. It can be observed that impact value reaches its maximum by adding the modifier, but on further addition, it reduces the strength.

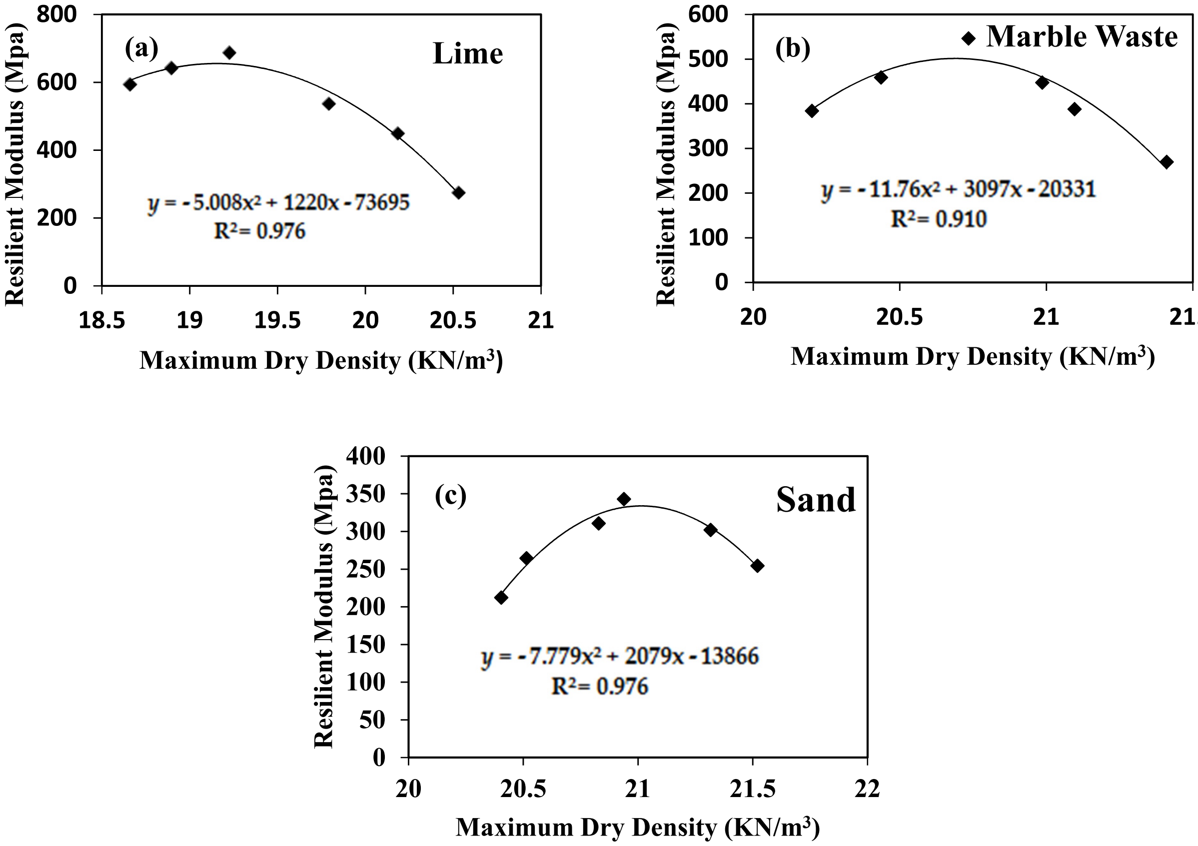

Figure 6. Effect of Maximum Dry Density on Resilient Modulus. (**a**) lime; (**b**) marble waste; (**c**) sand.

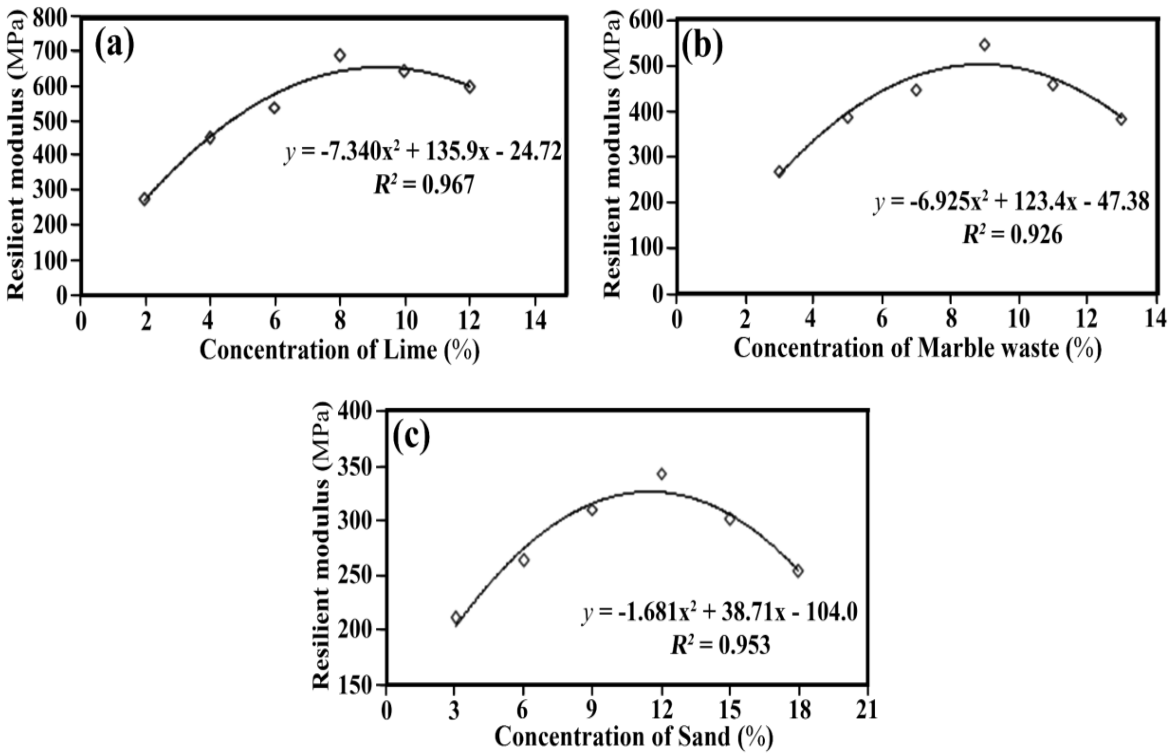

Figure 7. Effect of Concentration of Modifiers on Resilient Modulus. (**a**) lime; (**b**) marble waste; (**c**) sand.

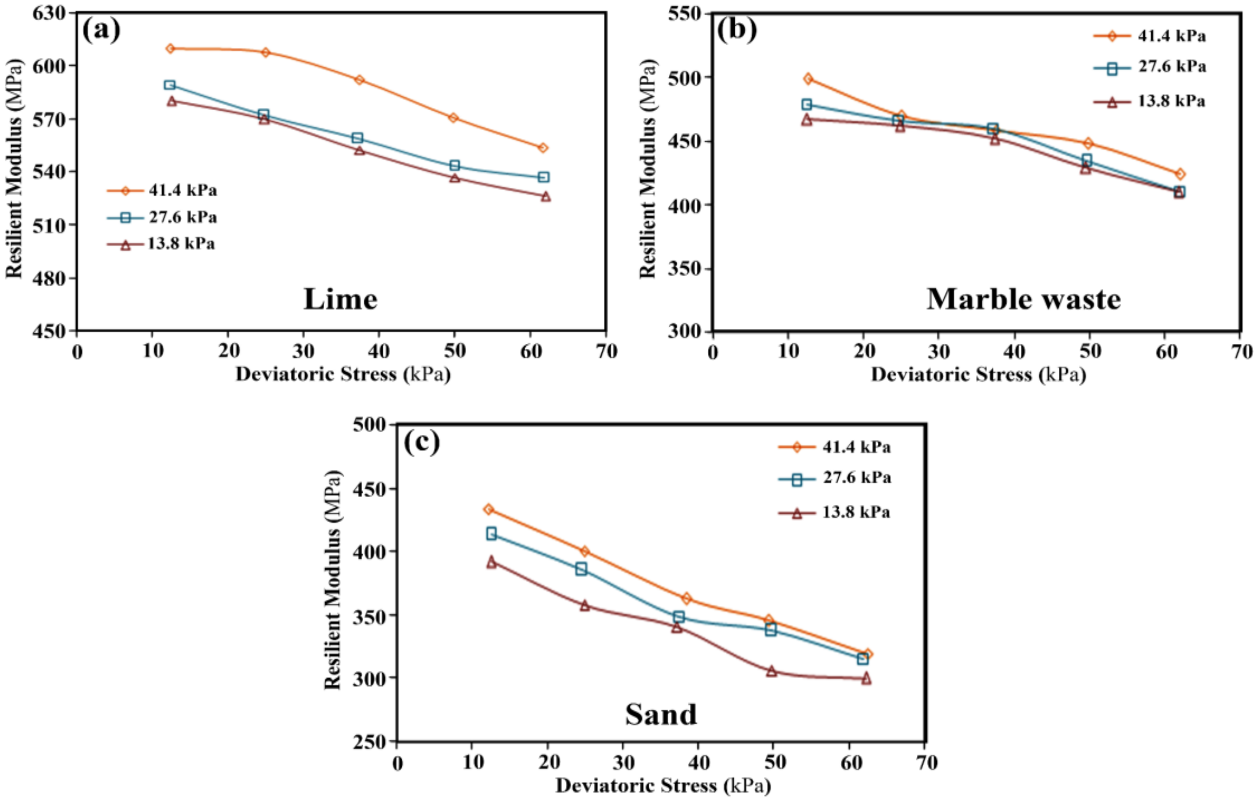

Figure 8. Effect of Deviatoric Stress on Resilient Modulus. (**a**) lime; (**b**) marble waste; (**c**) sand.

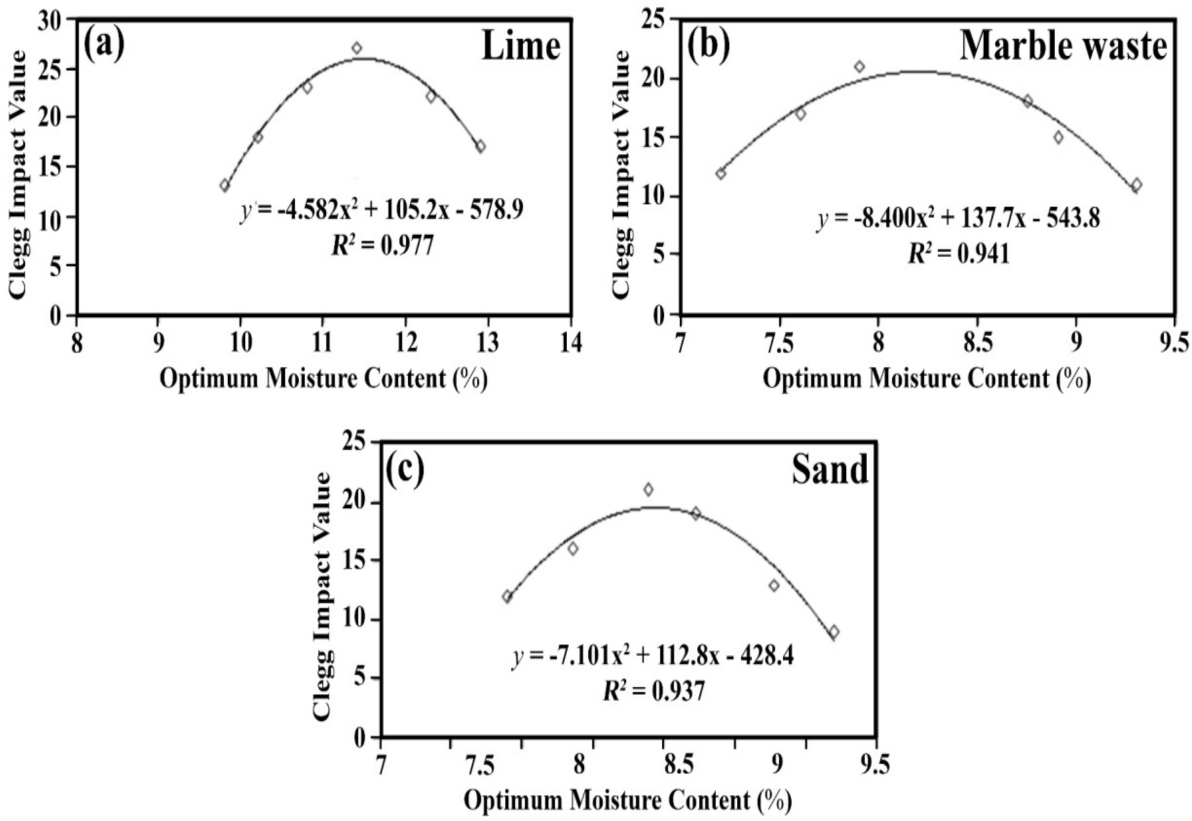

Figure 9. Effect of Optimum Moisture Content on Clegg Impact Value CIV. (**a**) lime; (**b**) marble waste; (**c**) sand.

Figure 10 is a representation of the relationship between the maximum dry density and Clegg Impact Value. CIV increased up to a certain level and then decreased on further addition. This result is consistent with previous researches carried out.

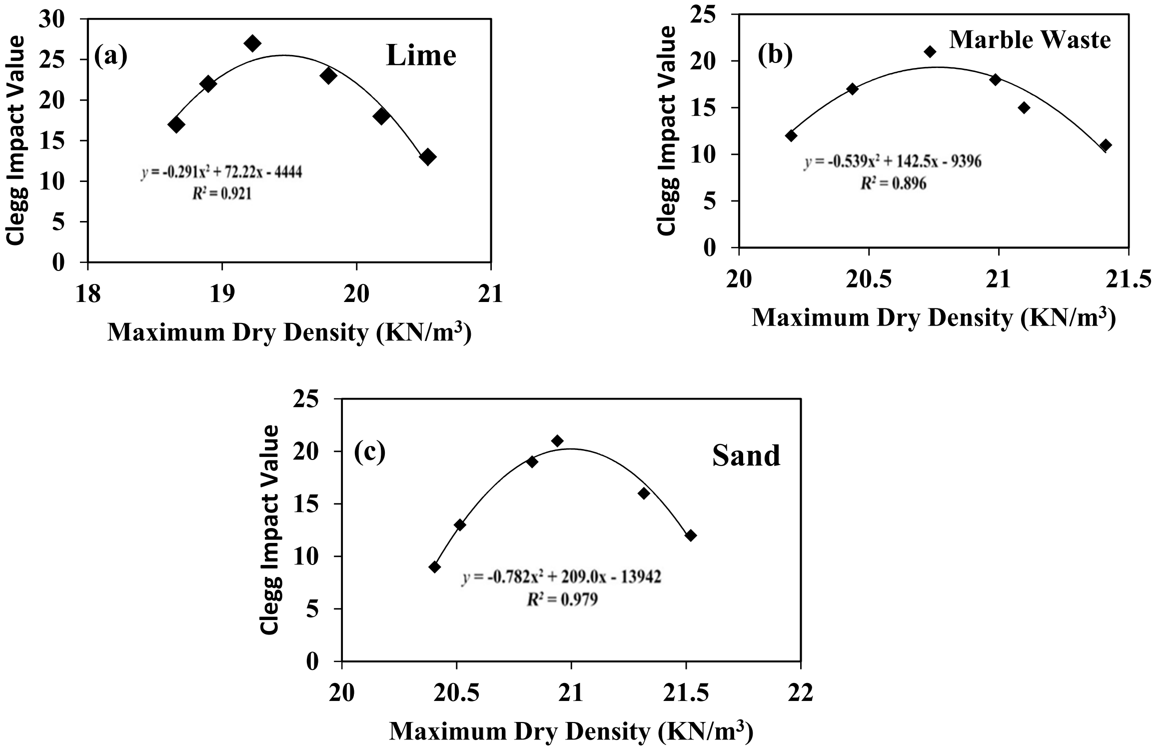

Figure 10. Effect of Maximum Dry Density Content on Clegg Impact Value (CIV). (**a**) lime; (**b**) marble waste; (**c**) sand.

Figure 11 is the detailed representation of effect of filler percentages on Clegg Impact Values. The graph shows that the impact value improves with increase in percentage of fillers up to a certain level and decreases afterwards. The graph helps to calculate the optimum quantity of modifier to improve the weak subgrade soil, and it is 8, 9 and 12% for waste lime, marble waste and sand, respectively.

Before modeling the data for the relationship between MR and CIV values, results obtained from this research has been compared with the previous researches. Table 6 presents the comparison of the outcome of this research with the list of previous researches, which are in line with the findings.

3.1. Data Modeling

Table 7 shows the outcomes of comparison between M_R (calculated in Lab) and MR (computed by Minitab software). The Equation (1) involves all the variables, and dependence of resilient modulus on all variables is very clear from Equation (1). From the Equation (1), it is quite obvious that the resilient modulus or subgrade stiffness is a function of "filler type", "percentage filler", "optimum moisture content", "maximum dry density" and "Clegg Impact Value". The equation does not specify a single type of variable; rather, it shows the dependence of stiffness modulus on different variables for any kind of the modifier. The comparison is laid in Table 7.

Table 6. Comparison of Results with Previous Researches.

Parameters and Their Effects	Result Obtained from This Research	Justified from Previous Research
Effect of additives on OMC and MDD	OMC shows the same trend for marble waste and sand modifier; as the percentage of modifier increases, OMC tends to decrease. In case of waste lime, increase in modifier percentage causes an increase in OMC, whereas MDD decreases. MDD in case of marble waste increases up to a certain level and then decreases afterwards. For lime and sand, MDD decreases with increase in percentage of respective modifier.	Same effect on the OMC and MDD has been observed [41–44].
Effect of Maximum Dry Density on Resilient Modulus	The MR values with lower water content higherthan those with high water contents.	The peak value of both CBR and MR was found on the dry side of optimum and at a dry density less than the maximum. Subgrade soil moisture condition has shown less significant influence on subgrade rutting if stabilized aggregate base layer is used instead of untreated granular base [45–47].
Effect of Percentage Modifier on Resilient Modulus	The modifiers improved the stiffness of the soil up to a certain level.	The soil clay content and percent of fines appear to play an important role in the effectiveness of enzyme-based stabilizer treatment. The limited effectiveness of enzyme (for low clay content soil) appears to be due to its surfactant-like characteristics [48]. The research works [49,50] evaluated the effectiveness of different percentages of hydrated lime, class C fly ash (CFA), and cement kiln dust (CKD) as soil stabilizers. The CKD-stabilized specimens exhibited a higher increase in M_R, and UCS values than the corresponding values of lime- and CFA-stabilized Specimens
Effect of deviatoric stress on Resilient Modulus	The relationship follows the ideal trends in case of all the three different confining pressures (decrease with increase in deviatoric stress).	MR decrease firstly and then remains constant with increasing the deviatoric stress [51]. MR decrease firstly and then increases with increasing the deviatoric stress. The effect of stress state is determined by equations relating resilient modulus at optimum moisture content to deviator stress so that the equation parameters represent the effect of soil type and its structure [46]
Effect of Maximum Dry Density Content on CIV	CIV and MDD values increased up to certainlevel and then CIV decreased while MDD goes increasing for further addition of modifier	Same trend has been observed for the analysis indicates a relatively strong correlation between CIV and CBR for forest subgrade soils [52]. Clayey and excessively wet soils have a significant negative impact on the correlation [53]
Effect of Concentration of Modifiers on CIV	It can be observed that impact value reaches its maximum by adding the modifier but onfurther addition, it reduces the strength	MR values are dependent of deviator and confining pressure, so in order to develop a relationship between the CIV and MR, resilient modulus should be written in the form of these stresses. Amount and size of the aggregates have remarkable effect of the resilient modulus. Fine additives can act as filler and damper to provide better interfacial bonding. Increase in the fine modifiers increases both CIV and MR values [54]

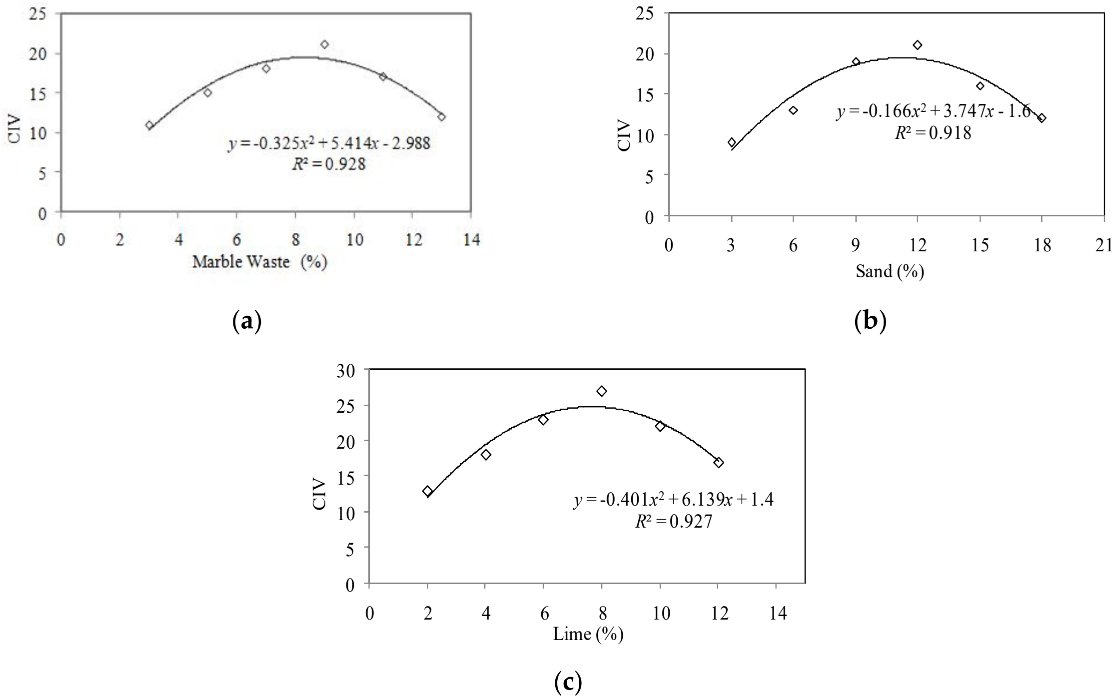

Figure 11. Effect of Concentration of Modifiers on CIV. (**a**) marble waste; (**b**) sand; (**c**) lime.

Table 7. Measured and computed M_R for Minitab developed equation.

Filler Type	% Filler	M_R (MPa) Measured in Lab	MR (MPa) Computed from Minitab Equation
Lime	2	275.12	267.98
	4	450.09	399.55
	6	537.27	540.64
	8	687.43	655.75
	10	642.62	643.47
	12	594.35	618.1
Marble Waste	3	270.09	280.19
	5	388.09	397.05
	7	447.57	493.73
	9	546.35	547.11
	11	459.15	427.43
	13	384.25	338.83
Sand	3	212.06	160.33
	6	264.25	235.41
	9	310.67	336.86
	12	342.78	386.5
	15	301.86	312.99
	18	254.41	259.51

The two values of the resilient modulus, i.e., measured and computed, were then compared in a graphical manner, and excellent results were observed. Figure 12 illustrates the comparison showing R^2 = 0.96 approximately depicts the excellent relationships between the computed (from Minitab) and measured (from NU-14 apparatus) modulus. The R^2 value clearly determines that the relationship developed is good and helpful to estimate the resilient modulus based on these variables for any kind of modifier.

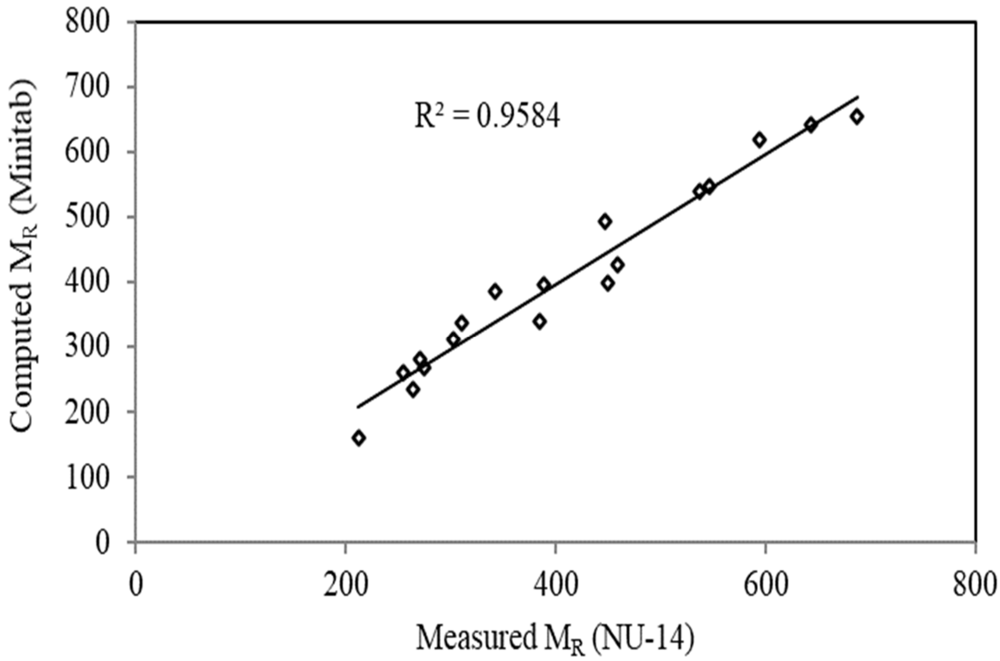

Figure 12. Measured M_R (NU-14) Versus Computed MR (Minitab equation).

Some other statistical graphs were also developed by the Minitab software and are shown in the Figure 13.

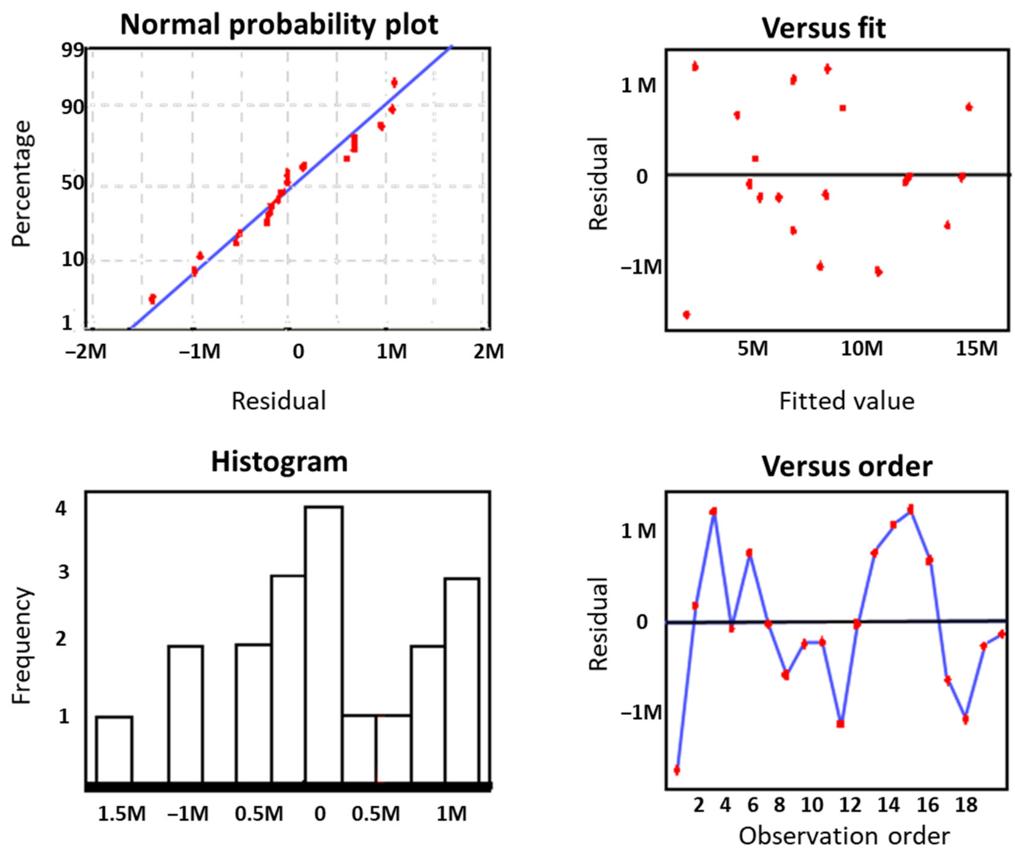

Figure 13. Residual Plots from Minitab.

All of the above graphs support the accuracy of relationship shown in Equation (1). The next relationship was then developed between the resilient modulus and CIV only, to know the effect of CIV alone on the modulus of stiffness.

3.2. Regression Model

Further, the resilient modulus was determined using the Equation (2), and it was then compared with the modulus measured from NU-14 apparatus (Table 8). The relationship was then used to compute the resilient modulus and compare it with the measured resilient modulus.

Table 8. Measured and Computed M_R for Regression Model Equation.

Filler Type	% Filler	M_R (MPa) Calculated in Lab	MR (MPa) Computed from Regression Model
Lime	2	275.12	314.46
	4	450.09	438.26
	6	537.27	562.75
	8	687.43	662.74
	10	642.62	537.80
	12	594.35	413.44
Marble Waste	3	270.09	265.20
	5	388.09	363.88
	7	447.57	438.26
	9	546.35	512.88
	11	459.15	413.44
	13	384.25	289.81
Sand	3	212.06	216.11
	6	264.25	314.46
	9	310.67	463.10
	12	342.78	512.88
	15	301.86	388.64
	18	254.41	289.81

The relationship of measured and computed resilient modulus is shown in Figure 14.

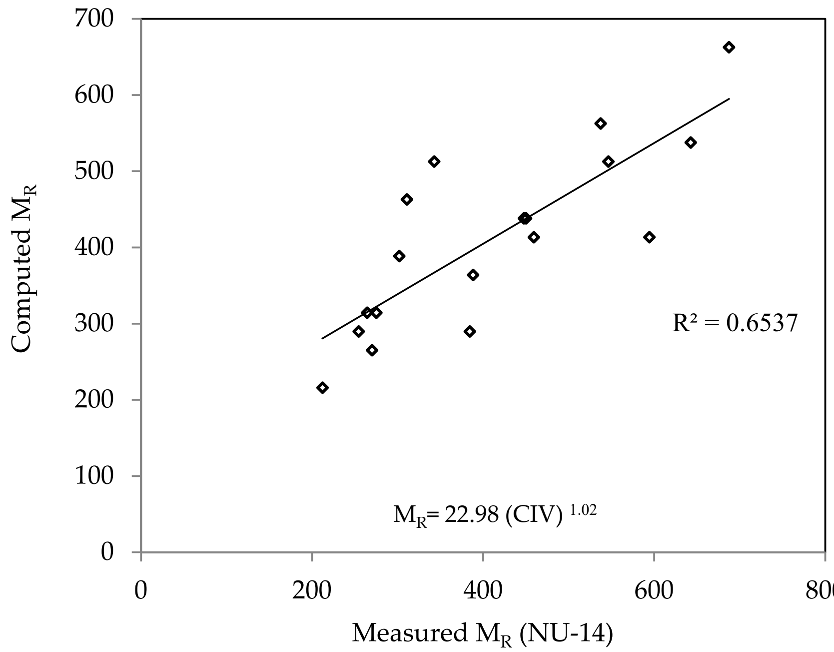

Figure 14. Measured M_R (NU-14) Versus Computed MR (Regression model equation).

The graph in Figure 14 shows the comparison of both the modulus values. Although the R^2 value of the graph is a little lower, the standard accuracy (Se/Sy) is very near to 0.1 and depicts a very good model. The accuracy of the results found by this equation is very high, making it a very reliable equation.

4. Conclusions

The aim of the research was to achieve the sustainability of transportation pavements by investigating the effect of different modifiers, i.e., lime(pulverized), waste marble and sand, on stiffness of weak subgrade soils. Research objectives were achieved by performing several laboratory tests to analyze the engineering properties of A-6 soil. Findings of this research study are presented as follows:

- All of the modifiers improved the stiffness of weak subgrade soil, but lime proved to be the most significant modifier because it improved the stiffness properties better than marble waste and sand.
- It is observed that the increment in percentages of lime and sand caused a drop in the value of maximum dry density of the soil samples, but the increment in marble waste percentage has enhanced the dry density of soil samples up to a certain extent and then decreased afterwards. With increasing the percentage of sand and marble waste, optimum moisture content decreased, but increase in lime percentage has increased the optimum moisture content. This significant increase in moisture content is due to its fineness, so the moisture sensitivity of subgrade soils can be dramatically affected by lime stabilization
- A strong relationship exists ($R^2 > 0.9$) between the MR determined from triaxial testing and CIV from Clegg impact test. The linear regression model shows that MR is a function of CIV, OMC, Filler type and MDD. Moreover, all the predictive techniques forecast the resilient modulus from other test parameters with good accuracy, but local linear regression better estimates the results.

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References

1. Kuhlman, T.; Farrington, J. What is sustainability? *Sustainability* **2010**, *2*, 3436–3448. [CrossRef]
2. Teltayev, B.B.; Liu, J.; Suppes, E.A. Distribution of temperature, moisture, stress and strain in the highway Распределение температуры, влажности, напряжений и деформаций в автомобильной дороге. *Mag. Civ. Eng.* **2018**, *83*, 202–213.
3. Zhou, C.; Huang, B.; Drumm, E.C.; Shu, X.; Dong, Q.; Udeh, S. Seasonal resilient modulus inputs for Tennessee soils and their effects on asphalt pavement performance. In Proceedings of the Transportation Research Board 92nd Annual Meeting, Washington, DC, USA, 13–17 January 2013.
4. Sadrossadat, E.; Heidaripanah, A.; Osouli, S. Prediction of the resilient modulus of flexible pavement subgrade soils using adaptive neuro-fuzzy inference systems. *Constr. Build. Mater.* **2016**, *123*, 235–247. [CrossRef]
5. Trivedi, J.S.; Nair, S.; Iyyunni, C. Optimum utilization of fly ash for stabilization of sub-grade soil using genetic algorithm. *Procedia Eng.* **2013**, *51*, 250–258. [CrossRef]
6. Al-Rawas, A.A.; Goosen, M.F.A. Expansive soils: Recent advances in characterization and treatment. *Proc. Monogr. Eng. Water Earth Sci.* **2006**, *130*, 391–402.

7. Шашкин, К.Г.; Улыбин, А.В. Soil stabilization and foundation restoration using an expandable polyurethane resin Стабилизация грунтов и восстановление фундамента с использованием расширяющейся полиуретановой смолы. *Mag. Civ. Eng.* **2018**, *82*, 68–80.
8. Sol-Sánchez, M.; Castro, J.; Ureña, C.G.; Azañón, J.M. Stabilisation of clayey and marly soils using industrial wastes: pH and laser granulometry indicators. *Eng. Geol.* **2016**, *200*, 10–17. [CrossRef]
9. Dimitris, D.; Meng, X.G. Utilization of fly ash for stabilization/solidification of heavy metal contaminated soils. *Eng. Geol.* **2003**, *70*, 377–394.
10. Onyelowe, K.C. Review on the role of solid waste materials in soft soils reengineering. *Mater. Sci. Energy Technol.* **2019**, *2*, 46–51. [CrossRef]
11. Castro-Fresno, D.; Movilla-Quesada, D.; Vega-Zamanillo, Á.; Calzada-Pérez, M.A. Lime Stabilization of bentonite sludge from tunnel boring. *Appl. Clay Sci.* **2011**, *51*, 250–257. [CrossRef]
12. Bekhiti, M.; Trouzine, H.; Rabehi, M. Influence of waste tire rubber fibers on swelling behavior, unconfined compressive strength and ductility of cement stabilized bentonite clay soil. *Constr. Build. Mater.* **2019**, *208*, 304–313. [CrossRef]
13. Singh, K.; Arora, V.K. Stabilization of Plastic Soil using Marble Dust, Rice Husk and Fly Ash. *Int. J. Adv. Technol. Eng. Sci.* **2019**, *5*, 276–281.
14. Yadav, A.K.; Gaurav, K.; Kishor, R.; Suman, S.K. Stabilization of alluvial soil for subgrade using rice husk ash, sugarcane bagasse ash and cow dung ash for rural roads. *Int. J. Pavement Res. Technol.* **2017**, *10*, 254–261. [CrossRef]
15. Ali, R.; Khan, H.; Shah, A.A. Expansive soil stabilization using marble dust and bagasse ash. *J. Sci. Res.* **2014**, *3*, 2812–2816.
16. Gelsefidi, S.; Alireza, S.; Mohammad, M.S.; Hasan, B.M. Application of nanomaterial to stabilize a weak soil. In Proceedings of the 7th International Conference on Case Histories in Geotechnical Engineering, Chicago, IL, USA, 29 April–4 May 2013; pp. 1–8.
17. Patel, M.A.; Patel, H.S. A review on effects of stabilizing agents for stabilization of weak soil. *Civ. Environ. Res.* **2012**, *2*, 1–7.
18. Kumar, J.K.; Kumar, V.P. Soil stabilization using E-waste: A retrospective analysis. *Mater. Today Proc.* **2020**, *22*, 691–693. [CrossRef]
19. Solanki, P.; Zaman, M.; Muraleetharan, K.K.; Timm, D. Evaluation of resilient moduli of pavement layers at an instrumented section on I-35 in Oklahoma. *Road Mater. Pavement Des.* **2009**, *10*, 167–188. [CrossRef]
20. Ghorbani, B.; Arulrajah, A.; Narsilio, G.; Horpibulsuk, S.; Leong, M. Resilient moduli of demolition wastes in geothermal pavements: Experimental testing and ANFIS modelling. *Transp. Geotech.* **2021**, *29*, 100592. [CrossRef]
21. Plati, C.; Cliatt, B. A sustainability perspective for unbound reclaimed asphalt pavement (RAP) as a pavement base material. *Sustainability* **2019**, *11*, 78. [CrossRef]
22. Ikeagwuani, C.C.; Nwonu, D.C.; Nweke, C.C. Resilient modulus descriptive analysis and estimation for fine-grained soils using multivariate and machine learning methods. *Int. J. Pavement Eng.* **2021**, *22*, 1–16. [CrossRef]
23. Ghorbani, B.; Yaghoubi, E.; Arulrajah, A. Thermal and mechanical characteristics of recycled concrete aggregates mixed with plastic wastes: Experimental investigation and mathematical modeling. *Acta Geotech.* **2021**, *16*, 1–16. [CrossRef]
24. Nazzal, M.D.; Tatari, O. Evaluating the use of neural networks and genetic algorithms for prediction of subgrade resilient modulus. *Int. J. Pavement Eng.* **2013**, *14*, 364–373. [CrossRef]
25. Al-Joulani, N. Effect of stone powder and lime on strength, compaction and CBR properties of fine soils. *Jordan J. Civ. Eng.* **2012**, *6*, 1–16.
26. Agrawal, V.; Gupta, M. Expansive soil stabilization using marble dust. *Int. J. Earth Sci. Eng.* **2011**, *4*, 59–62.
27. Nazzal, M.D.; Mohammad, L.N. Estimation of resilient modulus of subgrade soils using falling weight deflectometer. *Transp. Res. Rec.* **2010**, *2186*, 1–10. [CrossRef]
28. Ji, R.; Siddiki, N.; Nantung, T.; Kim, D. Evaluation of resilient modulus of subgrade and base materials in Indiana and its implementation in MEPDG. *Sci. World J.* **2014**, *2014*, 372838. [CrossRef]
29. Kim, D.; Kim, J.R. Resilient behavior of compacted subgrade soils under the repeated triaxial test. *Constr. Build. Mater.* **2007**, *21*, 1470–1479. [CrossRef]
30. Oh, J.H.; Fernando, E.G.; Holzschuher, C.; Horhota, D. Comparison of resilient modulus values for Florida flexible mechanistic-empirical pavement design. *Int. J. Pavement Eng.* **2012**, *13*, 472–484. [CrossRef]
31. Al-Rawas, A.A.; Hago, A.; Al-Sarmi, H. Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. *Build. Environ.* **2005**, *40*, 681–687. [CrossRef]
32. Al-Rawas, A.A.; Taha, R.; Nelson, J.D.; Beit Al-Shab, T.; Al-Siyabi, H. A comparative evaluation of various additives used in the stabilization of expansive soils. *Geotech. Test. J. GTJODJ ASTM* **2002**, *25*, 199–209.
33. Little, D.N.; Males, E.H.; Prusinski, J.R.; Stewart, B. Cementitious stabilization. In *Transportation in the New Millennium: Perspectives from TRB Standing Committees*; Committee A2J01; Committee on Cementitious Stabilization. TRB; National Research Council: Washington, DC, USA, 2000.
34. Prusinski, J.R.; Bhattacharja, S. Effectiveness of portland cement and lime in stabilizing clay soils. In *Transportation Research Record 1652*; TRB; National Research Council: Washington, DC, USA, 1999; pp. 215–222.
35. Bell, F.G. Lime stabilization of clay minerals and soils. *Eng. Geol.* **1996**, *42*, 223–237. [CrossRef]
36. Choksi, R.; Mishra, C.; Patel, N. Pursuance of waste marble powder to improve soil stabilization. *Int. Res. J. Eng. Technol.* **2018**, *5*, 1695–1698.
37. Cary, C.E.; Zapata, C.E. Resilient modulus for unsaturated unbound materials. *Road Mater. Pavement Des.* **2011**, *12*, 615–638. [CrossRef]

38. Perry, J.; MacNeil, D.J.; Wilson, P.E. The uses of lime in ground engineering: A review of work undertaken at the Transport Research Laboratory. In *Lime Stabilisation: Proceedings of the Seminar Held at Loughborough University Civil & Building Engineering Department on 25 September 1996*; Thomas Telford Publishing: London, UK, 1996; pp. 27–45.
39. Biczysko, S.J. Long-term performance of lime stabilised road subgrade. In *Lime Stabilisation: Proceedings of the Seminar Held at Loughborough University Civil & Building Engineering Department on 25 September 1996*; Thomas Telford Publishing: London, UK, 1996; pp. 62–74.
40. Little, D.N. *Stabilization of Pavement Subgrades and Base Courses with Lime*; Lime Association of Texas: McGregor, TX, USA, 1995.
41. Sabat, A.K.; Nanda, R.P. Effect of marble dust on strength and durability of Rice husk ash stabilised expansive soil. *Int. J. Civ. Struct. Eng.* **2011**, *1*, 939–948.
42. Bansal, H.; Sidhu, G.S. Influence of Waste Marble Powder on Characteristics of Clayey Soil. *Int. J. Sci. Res.* **2016**, *5*, 82–87.
43. Muthu Kumar, M.; Tamilarasan, V.S. Experimental study on expansive soil with marble powder. *Int. J. Eng. Trends Technol.* **2015**, *22*, 504–507. [CrossRef]
44. Yilmaz, F.; Yurdakul, M. Evaluation of marble dust for soil stabilization. *Acta Phys. Pol. A* **2017**, *132*, 710–711. [CrossRef]
45. Khoury, N.; Brooks, R.; Zaman, M.M.; Khoury, C.N. Variations of resilient modulus of subgrade soils with postcompaction moisture contents. *Transp. Res. Rec.* **2009**, *2101*, 72–81. [CrossRef]
46. Chen, W.-B.; Feng, W.-Q.; Yin, J.-H. Effects of water content on resilient modulus of a granular material with high fines content. *Constr. Build. Mater.* **2020**, *236*, 117542. [CrossRef]
47. Rahman, M.M.; Gassman, S.L. Moisture effect of subgrade resilient modulus on pavement rutting. In Proceedings of the Transportation Research Board 97th Annual Meeting, Washington, DC, USA, 7–11 January 2018.
48. Velasquez, R.A.; Marasteanu, M.O.; Hozalski, R.M. Investigation of the effectiveness and mechanisms of enzyme products for subgrade stabilization. *Int. J. Pavement Eng.* **2006**, *7*, 213–220. [CrossRef]
49. Moazami, D.; Yusoff, Z.M.; Muni, R.; Hamid, H. Effect of stabilizers on stiffness modulus of soil layers: A review. *Int. J. Phys. Sci.* **2013**, *8*, 1602–1610.
50. Solanki, P.; Khoury, N.N.; Zaman, M.M. *Engineering Properties of Stabilized Subgrade Soils for Implementation of the AASHTO 2002 Pavement Design Guide*; Federal Highway Administration: Washington, DC, USA, 2009.
51. Li, D.; Selig, E.T. Resilient modulus for fine-grained subgrade soils. *J. Geotech. Eng.* **1994**, *120*, 939–957. [CrossRef]
52. Fairbrother, S.; McGregor, R.; Aleksandrov, I. Development of a correlation equation between Clegg impact values and california bearing ratio for In-field strength assessment of forest road subgrades. In Proceedings of the 33th Annual Meeting of the Council on Forest Engineering: Fueling the Future, Auburn, AL, USA, 6–9 June 2010.
53. Gulen, S.; McDaniel, R.S. *Use of Clegg Hammer for Compaction Control*; The National Academies of Sciences, Engineering, and Medicine: Washington, DC, USA, 1990.
54. Saberian, M.; Li, J.; Nguyen, B.T.; Setunge, S. Estimating the resilient modulus of crushed recycled pavement materials containing crumb rubber using the Clegg impact value. *Resour. Conserv. Recycl.* **2019**, *141*, 301–307. [CrossRef]