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Effect of illite on the mechanical properties of subgrade soil under varying surcharge loads

Kashif Riaz *, Naveed Ahmad

University of Engineering & Technology, Taxila, Pakistan

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ABSTRACT

Due to its non-expanding properties, presence of Illite mineral in subgrade soil is investigated particularly on California bearing ratio (CBR), resilient modulus (M_R) and swell potential. Multiple samples of stiff and weak subgrade soils with varying illite percentages were tested under six different surcharge loads ranging from 2.27 to 13.8 kg. Mineralogical analysis is performed using X-ray diffractometer and M_R of soil is assessed using Ultrasonic pulse velocity (UPV) technique. Results showed a positive correlation between Illite percentage and both CBR and M_R value. The soil with higher Illite content tends to exhibit higher CBR and M_R values while those with higher montmorillonite content show lower values even with more Illite content. The CBR and M_R values increases from 8.4% to 19 % and 139 MPa–315 MPa for stiff soil and 3.8%–11.7 % and 23 MPa–83 MPa for weak soil, respectively when the surcharge load was increase from to 2.27–13.8 kg. Additionally, a decrease in swell potential was observed from 1.64% to 1.09 % for stiff soil and 1.39%–0.84 % for weak soil with an increase in Illite percentage. The study also developed an improved relationship for predicting resilient modulus based on CBR value, showing a strong correlation with equations developed by many researchers in the past.

1. Introduction

Illite is the most common clay minerals present in soils which affect the mechanical properties of soil i.e. M_R and CBR depending upon various factors such as percentage of Illite present in soil [1]. Soil with a higher percentage of illite has higher cohesion and low plasticity and permeability [2]. Its percentage varies depending upon the geological conditions of the area which affect its behavior under different surcharge loads.

Quantifying clay minerals is crucial for assessing clay-rich rock and soil, but it's a challenging task due to their complex structures and varied compositions [3]. Over the past century, X-ray diffraction (XRD) has emerged as a vital analytical method for qualitatively and quantitatively studying geological samples [4]. Compared to other techniques such as Fourier transform infrared spectroscopy (FTIR), chemical analysis, and electron microscopy, XRD analysis is widely considered the most suitable method for routine quantitative analysis [5,21]. However, quantifying certain minerals, especially clay minerals, remains a significant challenge due to their diverse chemical compositions, preferred orientation, structural disorder, and extensive structural diversity [6].

Clay mineralogy research involves the identification and quantification of clay minerals in soils, sediments, and rocks using various analytical techniques, such as X-ray diffraction (XRD) and infrared spectroscopy [7,8]. It provides valuable insights into soil properties, weathering processes, and environmental conditions, helping researchers and practitioners make informed decisions in a wide range of

* Corresponding author.
E-mail address: Kashif.riaz@uettaxila.edu.pk (K. Riaz).

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applications. This note provides an overview of clay minerals and their significance in research [7]. The mineral composition of clay minerals, including kaolinite, Illite, montmorillonite, chlorite vermiculite significantly influences these parameters [9].

Most of the highway system in Pakistan consists of flexible pavement. Various approaches exist for the design of flexible pavement. The CBR test is a widely used empirical approach for the construction of flexible pavements [10]. The CBR value acquired during this examination is a crucial component in several methodologies for designing flexible pavements [11]. With increasing urbanization, there is a greater emphasis on achieving desirable pavement strength while minimizing production and construction costs [12]. Various parameters such as maximum dry density, CBR, field dry density, Unconfined compressive strength (UCS) and modulus of subgrade reaction are considered in relation to the subgrade material [13].

AASHTO T-193 recommends a surcharged weight of 4.54 kg on CBR mould. However, in industry the use of surcharge weight in CBR testing is not well-defined. The overburden pressure resulting from the weight of the pavement on the soil is simulated using surcharge weight [14]. Razouki [15] suggested that a surcharge weight of 2.27 kg is suitable for pavement thicknesses of 63.5 mm, but the weight on CBR mould should not be less than 4.5 kg.

To calculate the surcharge weight for CBR testing in the design, contractors and construction companies take the thickness of pavement layers above the subgrade into consideration [14]. This approach often involves using higher surcharge weights compared to the standard weight used in a CBR test. However, using increased surcharge weight can result in variations in soil CBR values. Therefore, it is important to investigate that how varying surcharge weights effect the commonly used soil types in pavement construction in Pakistan.

Razouki [15] conducted a study on roadbed sand with 39 % gypsum content by applying a 200 N surcharge weight on CBR mould and subjecting them to cyclic soaking and drying processes. The study showed that the CBR values increased during the drying cycle and decreased during the soaking cycle and the deformation properties of gypsi-ferous soil were significantly affected by the soaking period. The effect of soaking period on subbase soil with a surcharge weight of 4.5 kg was also investigated by Jaleel [16] and the research concluded that the bearing capacity of the subbase soil decreased as the soaking period was prolonged.

A study conducted by Razouki [17] focused on gypsi-ferous soils and the impact of soaking time and surcharge weight on CBR and M_R. The research involved testing clay samples by applying surcharge loads of 45 N, 178 N, and 312 N and soaked them for different durations ranging from 0 to 180 days. The findings indicated a direct relationship between surcharge weight and M_R, showing an increase in resilient modulus with higher surcharge weights. However, a decrease in the resilient modulus was seen with increasing soaking time. Razouki [18] also explored the behavior of silty soil under various surcharge loads of 44.5 N, 89 N, 178 N and 267 N and observed that increasing surcharge weight led to an increase in CBR value. Previous studies have primarily focused on examining the influence of surcharge load on soil strength [15].

The presence of stabilizers and admixtures can have a combined effect on soil performance [14]. Some authors have investigated the effects of moisture content variation, compaction effort and soaking period on the resilient modulus and California Bearing Ratio (CBR) of sand rich with gypsum or other stabilized soils [19]. Therefore, there is a need to evaluate the behavior of both strong and weak subgrade soils when subjected to varying surcharge weights [20].

Relationships for estimating the resilient modulus of subgrade material have been developed in order to reduce the cost and duration of road construction projects and to make engineer's work easier [21]. Although many relationships have been developed by researchers to evaluate the resilient modulus from soil index properties, unconfined compressive strength (UCS), Maximum Dry Density (MDD), Optimum Moisture Content (OMC), etc. However, the relationship between CBR (California Bearing Ratio) and resilient modulus is generally favored. Both are considered strength parameters, and resilient modulus is often better predicted from CBR.

Table 1 summarizes past studies focusing on the development of different models. Firstly, the following M_R-CBR relationship was developed by Heukelom [22] by performing Cyclic triaxial test on multiple types of soil. The second relation was developed by Heukelom and Klomp in 1962 and AASHTO Design guide [23] showed that equation is valid for the fine-grained soil having CBR≤10. Green & Hall [24] proposed the relation by applying wave propagation technique on in-situ soil. Powell [25] also used wave propagation technique for soil having CBR 1 to 12. Abubaker [14] gave the relationship for weak and stiff soil by apply different surcharge

Table 1
Summary of literature studies focusing on the development of different models.

Reference	Developed modelled	Conditions/Soil Type
Heukelom and Foster (1962)	M_R (psi) $= 1565$ CBR	Multiple types of Soil
Heukelom and Klomp (1962)	M_R (psi) $= 1500$ CBR M_R (MPa) $= 10.345$ CBR	Multiple types of Soil having CBR≤10
Green and Hall (1975)	M_R (psi) $= 5409 CBR^{0.71}$ M_R (MPa) $= 37.3 CBR^{0.71}$	Wave Propagation and in-situ CBR
Powell (1984)	M_R (psi) $= 2554 CBR^{0.64}$ M_R (MPa) $= 17.6 CBR^{0.64}$	Wave Propagation and in-situ CBR for soil having 1≤CBR≤12
Raja Abubakar 2022	M_R (MPa) $= 14.74 CBR^{0.72}$ M_R (MPa) $= 40.87 CBR^{0.68}$	Wave propagation method on A-4 and A-2-4 Soil, respectively
Razouki (2002)	M_R (MPa) $= 40.87 CBR^{0.68}$	Silty sandy Subgrade soil(A-2-4) at different surcharge loads.
Razouki (2017)	M_R (MPa) $= 40.87 CBR^{0.68}$	Gypsum and sand modified soil at different surcharge loads
Garver and Hobel (2015)	M_R (MPa) $= 10.342 * $ CBR	Multiple types of Soil
Razouki (2004)	M_R (MPa) $= 5.05$CBR $+ 2.9173$	Weak soil (A-7-6)

load on soil sample. types of soil. Past research have shown that various M_R-CBR correlations were developed but the most commonly used relationship was created by Heukelom and Klomp [26].

Many researchers developed a model to predict M_R of the subgrade soil based on CBR value. Generally, these models cannot be used for the unique soil composition. This research developed an improved correlation between M_R-CBR based on the specific geological variation where diverse mineral composition i.e Illite percentage prevails across the region. This study not only develops a model between CBR-M_R for the local soils but also reveals novelty on the influence of Illite percentage on the M_R. This region-specific approach will provide more accurate results to determine the soil strength parameter which is very crucial in the design of pavements. This study focuses on two main objectives. Firstly, it aims to analyze the impact of varying Illite percentage and increased surcharge weight on the CBR, swell percent and M_R of stiff and weak subgrade soils collected from different geological locations. Secondly, it seeks to compare the CBR-M_R relationships commonly used in the field with those obtained through laboratory-based research of different soil types.

2. Experimental program

Primarily samples were taken from different geological strata having variety in mineral composition, especially with varying illite percentages. Disturbed soil samples were collected from six districts in KPK, namely Bajaur(S1), Chakdara(S2), Takht Bhai(S3), Karak (S4), Swabi(S5), and Nowshera (S6) as shown in Fig. 1. The main purpose of selecting these sites is the variation in Illite content. The samples were taken from a depth of approximately 1 m below the ground surface. Several tests were conducted on these soil samples to determine their index properties (L.L,P.L &P.I) [27], moisture content [28] and classify them according to the AASHTO Soil classification system [29].

Optimum moisture content and maximum dry density of soil samples were measured using modified proctor tests in accordance with ASTM D 1557 [30]. For the CBR (California Bearing Ratio) test, the samples were compacted at 95 % of the MDD according to AASHTO T193 [11].The resilient modulus was assessed using a non-destructive testing method called ultrasonic pulse velocity, both before and after soaking the CBR samples. Compression and shear wave travel times were measured to calculate the resilient modulus before and after each soaking period [31]. To establish a relationship between the resilient modulus and CBR, empirical correlation was obtained through single linear regression analysis. This analysis aimed to provide insights into the connection between these two parameters. Fig. 2 represents the sequential steps involved in the research work.

3. Results and discussion

3.1. X-ray diffraction test

The XRD analysis was conducted using an advanced X-ray Diffractometer [32]. This instrument utilizes X-ray beams to interact with the sample, causing diffraction patterns that are then detected and analyzed to determine the mineral phases present in the soil. 50 g of multiple soil samples from different geological locations were taken for analysis. These locations were carefully chosen to capture the geological diversity of the area, providing a comprehensive insight into the soil's mineral composition across different terrains. One of X-ray diffractometer results is shown in Fig. 3. Following the XRD analysis, Match-2 software was used for interpretation and quantification of the various minerals found in the soil [32].

Table 2 represent the matching phases of the major clay minerals including their chemical formula and quantity obtained from Match-2 software by analysing XRD data for each soil. X-ray diffraction (XRD) analysis revealed that Illite was present in higher quantity compared to other minerals quantity. The quantity of vermiculite and montmorillonite was observed too less while kaolinite and Quartz quantity was fluctuating randomly due to which they were not considered.

Fig. 1. Collection points of soil samples.

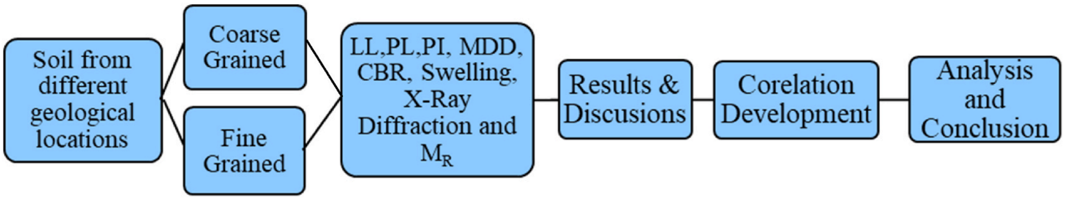

Fig. 2. Scope and Methodology of the work.

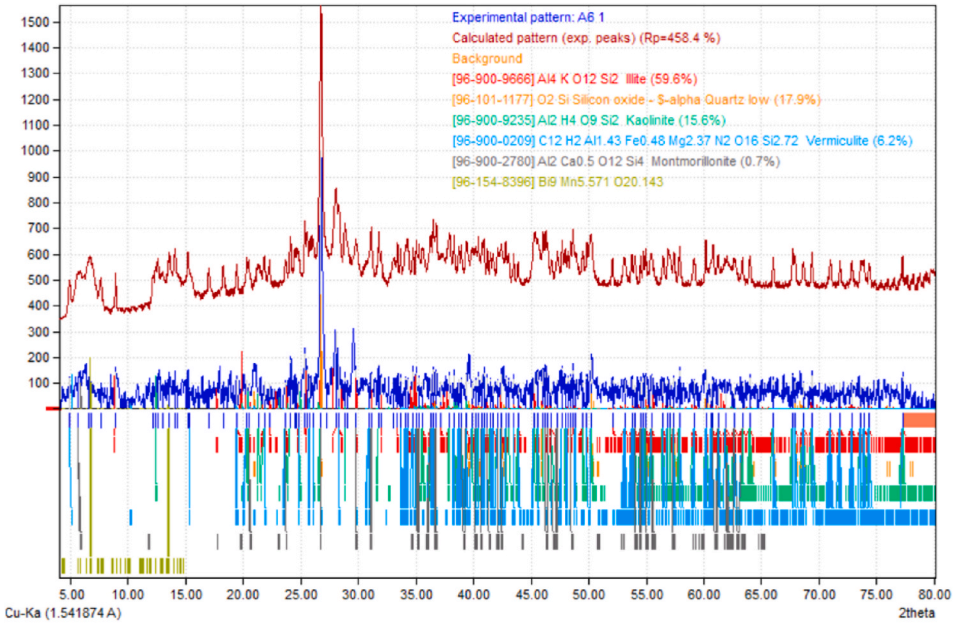

Fig. 3. Results of X-rays diffractometer.

Table 2
Quantity of clay minerals.

Soil Sample	Illite (%)	Quartz (%)	Kaolinite (%)	Montmorillonite (%)	Vermiculite (%)
S1	59.6	17.9	15.6	0.7	6.2
S2	51.8	23.4	23.4	1.0	1.8
S3	48.7	25.9	20.3	3.1	1.9
S4	48.6	25.4	17.3	33.7	6.3
S5	46.0	22.0	27.6	21.0	2.7
S6	39.9	34.7	16.2	9.0	7.7

Table 3
Geotechnical properties of different geological locations.

Properties	S1	S2	S3	S4	S5	S6
Illite %	59.6	51.8	48.7	48.6	46	39.9
Liquid limit	37	39	24	30	32	36
Plastic Limit	21	22	7.7	11	17.5	12
Plasticity Index	16	17	16.3	19	14.5	24
MDD(g/cc)	1.94	1.96	1.97	1.82	1.85	1.80
OMC (%)	10.5	9.5	9	13.8	13	14.5
AASHTO Classification	A-2-6	A-2-6	A-2-6	A-6	A-6	A-6

3.2. Index properties

Soil Index properties, gradation and moisture content were determined to classify the soil samples. For soil having less illite percentage is selected to determine the influence of surcharge load on its CBR value. For comparison soil with higher percentage of illite, which is categorized as stiff soil is selected as the second type. To prepare the CBR sample, optimum moisture content was calculated using dry density vs moisture content graph. Results of index properties, maximum dry density and optimum moisture content are tabulated in Table 3.

3.3. CBR testing

Three replicate samples of each were compacted using different numbers of blows per layer (10, 30, and 65 blows). The samples were prepared in 6inch molds and compacted in 5 layers using a10lbs hammer with an 18inch height of fall. After preparation, the CBR molds were submerged in a water tank for 96 h to measure the soil's swell potential. The soil's swelling was determined using dial gauges with an accuracy of 0.01 mm. While soaking, six different surcharge loads were applied to each CBR mould ranging from 2.27 kg to 13.8 kg with increment of 2.27 kg on each sample. A total of 108 CBR molds were prepared at different surcharge weights having different percentages of Illite content.

It can be seen from Fig. 4 that higher Illite quantity lead to the higher CBR value and less swelling potential because it has good shear strength and can contribute to the soil's cohesion and load-bearing capacity [6,33]while higher Montmorillonite quantity in soil has lower CBR value although Illite quantity higher due to its swelling and expansive characteristic it reduces CBR values. A significant increase in CBR value and decrease in swelling percentage with an increase in compaction effort (10–65 blows/layer) at each surcharge load was seen. The CBR value of S5 increased from 1.56 to 4.37 at 4.54 kg surcharge load when the compactive effort was increase from 10 to 65 blows per layer. Similarly, swelling potential decreased from 1.63 % to 1.46 % with an increase in compactive effort.

Fig. 5 illustrates the impact of surcharge weight on the CBR values at 95 % of maximum dry density. The CBR values of the fine-grained soil from different locations showed a significant increase when the surcharge load increased from 2.27 kg to 13.8 kg. For the fine-grained soil, the CBR values increased from 2.2 % to 11.7 %(S4), 1.95 %–8 % (S5) and 2.3 %–10.1 % (S6) with the corresponding increase in surcharge weight. The stiffening of the soil within the CBR molds because of the additional pressure from the surcharge weight can be related to the increase in CBR value. The rise in CBR value for the fine-grained soil can also be explained by factors such as clay mineralogy, index properties and the compactive effort which align with findings reported by Nagaraj [34]. The decrease in voids ratio is another potential factor contributing to increased CBR values with larger surcharge weight. This reduction leads to an increase in the density of the weak soil, thereby enhancing the soil's strength.

Similarly, CBR of stiff soil, which is considered a good subgrade material showed significant increased with increasing surcharged weight increased from 2.27 kg to 13.8 kg. For stiff soil, the CBR values increased from 5.5 % to 15.3 % (S1), 6.9 %–19 % (S2), and 6 %–13.6 % (S3), with the corresponding increase in surcharge weight. This represents more than double the increase in CBR values. A-2-6, a sandy clay soil, shows an increasing trend in CBR values that can be attributed to its increased internal frictional angle. Sandy clay soils can bear greater overburden weights on their major principal axis, leading to improved CBR values. Similar results have been reported in previous studies on sandy soils. Strength ratios of the CBR samples were determined to compare the behavior of weak and strong soils under the same surcharge weight, which provided an indication of the relative increase in the CBR value with each incremental load [15]. Fig. 6 represents strength ratio of different Illite percentages under varying surcharge loads, which shows that weak soil experiences a greater impact on its strength from surcharge weight compared to the strong soil having different percentage of illite content. It may be noted that the CBR value of weak soil increased 3.4 times when the surcharge weight reached 13.8 kg. In contrast, the same increase in surcharge weight only doubled the CBR value of the stiff soil. The difference in the CBR value of the same type of soil from various locations is caused by variations in mineral composition of soil. Overall, the study highlights the influence of surcharge weight on CBR values and provides insights into the factors contributing to the observed changes in soil behavior.

From the regression analysis, equations obtained for each soil can be used to determine CBRs at different surcharge weight if the CBR at 4.5 kg surcharge weight is known.

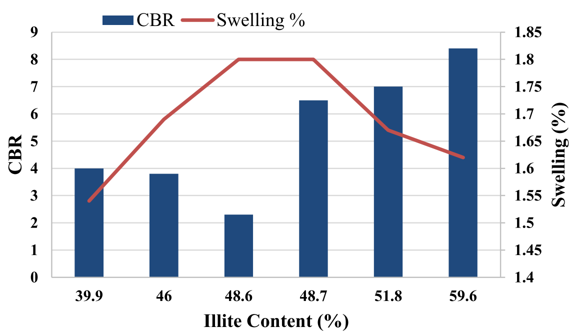

Fig. 4. Effect of illite on CBR and swelling.

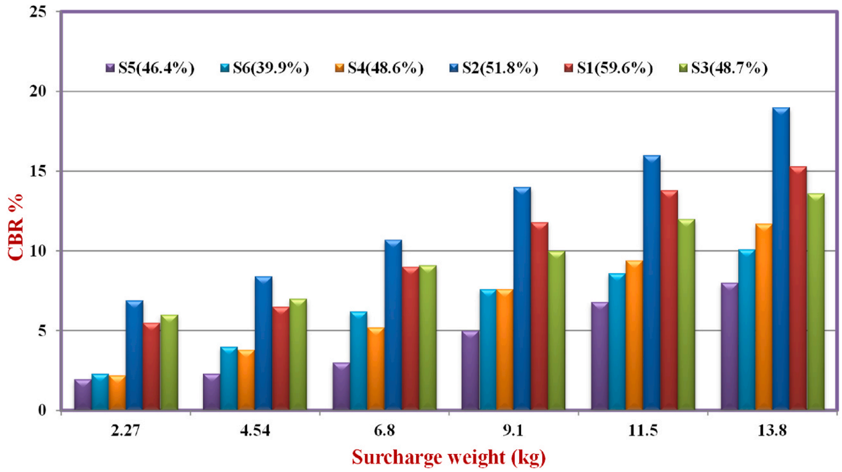

Fig. 5. Influence of varying surcharge load on CBR Value.

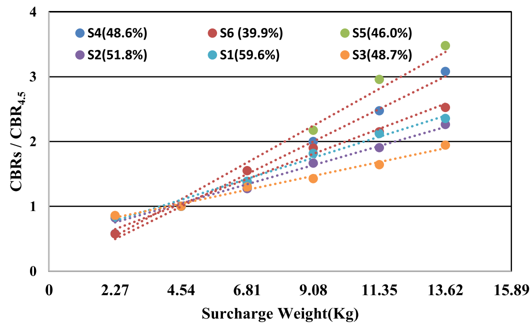

Fig. 6. Strength ratio of Illite percentage at different surcharged weights.

$$\textbf{For A} - \textbf{2} - \textbf{6 soil } CBR = (0.1202S + 0.5176) * CBR_{4.5} \tag{1}$$

$$\textbf{For A} - \textbf{6 soil } CBR = (0.2104 + 0.0921) * CBR_{4.5} \tag{2}$$

"s" represents applied surcharge weight in kgs.

The influence of varying surcharge loads on the swelling potential of the soil was also examined. Fig. 7 represents the decrease in the swell percent with the increased surcharge load and compaction effort (65blows/layer). A similar trend was observed in the swelling potential with the increased surcharged weight at a lesser number of blows per layer (10 & 30). Among the various surcharge weights, the highest compaction effort of 65 blows per layer results in the least amount of swelling. It can be noted that A-6 soil exhibits

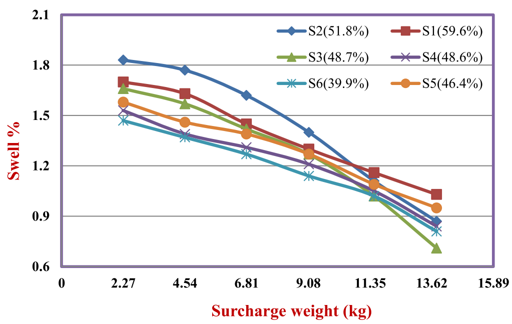

Fig. 7. Swelling potential at different surchage loads.

more swelling than A-2-6 soil at different locations. According to NHA specifications, the recommended swell potential value for subgrade material is 0.3 % [27]. For A-6 soil, the swelling potential at a standard surcharge weight of 4.54 kg was 1.39 %(S4), 1.37 % (S5), and 1.46 %(S6) respectively. At 13.8 kg, the swelling potential decreased to 0.84 %(S4), 0.95 %(S5) and 0.81 %(S6) at the same locations. Similarly, for A-2-6 soil, the swelling potential at a standard surcharge weight of 4.45 kg was 1.68 %(S1), 1.64 %(S2) and 1.61 %(S3) respectively. With an increase in surcharge weight to 13.8 kg, the swelling potential decreased to 1.03 %(S1), 1.09 %(S2), and 1.01 %(S) at the same locations. The dry density of the soil increases due to higher number of blows per layer, resulting in a reduction in the swelling potential. Similar findings were reported by Ref. [19], who observed a decrease in clayey soil swelling with higher number of blows per layer at a same moisture content. Due to the greater compactive effort, voids ratio between soil particles decreases, which results in a reduction in swelling potential.

3.4. Ultrasonic pulse velocity test (UPV)

The ultrasonic pulse velocity technique [31,35] is commonly employed in geotechnical engineering to assess dynamic strength parameters such as elastic modulus, shear modulus and Poisson's ratio [8]. The direct transmission approach is considered the most suitable method for this purpose. During the test, transducers of UPV are positioned on opposite faces of the sample. The fundamental principle of this test involves determining the time taken by waves to pass through the soil sample. The wave transmission technique is utilized to calculate Poisson's ratio (μ) and the Resilient modulus. To achieve this, compression velocity (V_c) and shear velocity (V_S) of waves were determined [36]. The following equations were used to calculate the values of the Resilient modulus as employed by the [17,31] according to (ASTM D2845).

$$M_R = \frac{[\rho V_c^2 (3V_c^2 - 4V_s^2]}{(V_c^2 - 2V_s^2)} \tag{3}$$

Where, V_c & V_s = Velocities of wave (m/s), ρ = Density (kg/m^3), M_R = Resilient modulus (MPa)

Compression and shear velocities [31] were measured using transducers placed on each side of mould before and after 96 h of soaking shown in Fig. 8. To minimize the error in the reading due to steel molds and surcharge weights, the transducers were placed in direct contact with the soil surface. CBR tests were performed on the samples after UVP according to Ref. [37] and CBR values were determined at 95 % of the maximum dry density. Fig. 8 represents the reduction in compression velocity after soaking at standard surcharge weight of 4.5 kgs.

The findings from the UPV test are presented in Fig. 9. The study indicates that greater material density corresponds to higher wave velocities. Moreover, when the compaction effort is increased to 65 blows/layer, the velocities significantly surpass those at 30 and 10 blows/layer. For A-6 soil, the compression velocity at a standard surcharge weight of 4.54 kg was 194 m/s(S4), 161 m/s(S5), and 150 m/s(S6) respectively. At 13.8 kg, the compression velocity increased to 288 m/s(S4), 218 m/s(S5) and 237 m/s(S6) at the same locations. Similarly, for A-2-6 soil, the compression velocity at a standard surcharge weight of 4.45 kg was 400 m/s(S1), 418 m/s(S2) and 379 m/s(S3) respectively. With an increase in surcharge weight to 13.8 kg, the compression velocity increased to 488 m/s(S1), 533 m/s(S2) and 452 m/s(S3) at the same locations. This rise in velocity corresponds to an increase in CBR values, due to reduced porosity and increased soil density under greater surcharge load. As the surcharge load increases from 2.27 kg to 13.8 kg, both velocities and CBR values exhibit an upward trend. A-2-6 soil exhibits higher velocities and CBR values compared to A-6 soil. The increased strength of the soil under heavier loads can be attributed to the increase in wave velocities. This increased in soil stiffness ultimately leads to higher resilient modulus (M_R) values for soil samples.

Table 4 represents the calculations of resilient modulus of each soil using equation (3) at different surcharge loads. Resilient modulus is increased from 6 MPa to 83 MPa for weak soil and 96 MPa–315 MPa for stiff soil. On average M_R of weak & stiff soil is increased 4.5 times &1.5 times respectively. Resilient modulus increases due to higher wave velocities with increasing surcharge from 2.27 to 13.8 kgs. It can be seen from Table 4 that with increasing Illite percentage and surcharge load from 2.27 kg to 13.8 kg, both CBR and M_R values increase. For A-2-6 soil, a greater percentage of Illite content shows better improvement in CBR and M_R as compared to

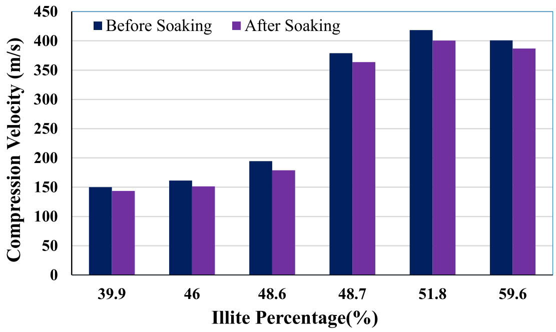

Fig. 8. Effect of Illite on compression velocity.

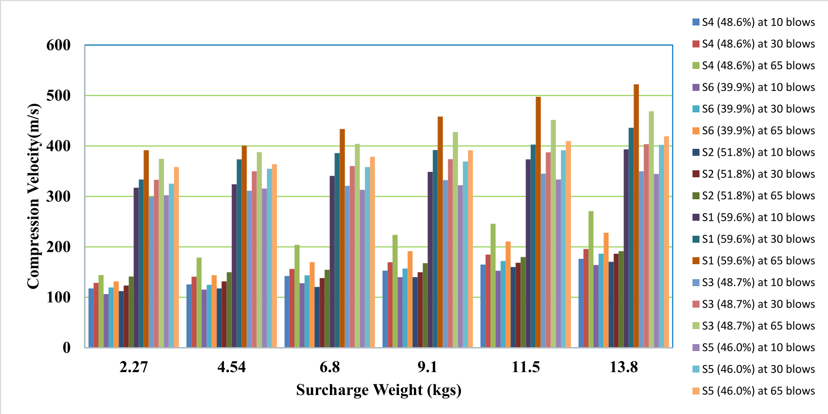

Fig. 9. Effect of surcharge on Compression velocity.

Table 4
Calculations of resilient modulus using UPV.

Surcharge Weight(kgs)	Illite (%)	CBR @ 95 % MDD	M_R @ 95 % MDD (MPa)	Illite (%)	CBR @ 95 % MDD	M_R @ 95 % MDD (MPa)
2.27	48.6	2.2	13	51.8	6.9	122
4.54		3.8	23.4		8.4	139
6.8		5.2	42.3		10.7	156
9.1		7.6	59		14	179
11.5		9.4	65.4		16	235
13.8		11.7	83		19	315
2.27	39.9	2.3	7.5	59.6	5.5	96
4.54		4	13.1		6.5	102
6.8		6.2	22.4		9	128
9.1		7.6	32.7		11.8	160
11.5		8.6	36.4		13.8	205
13.8		10.1	44.5		15.3	270
2.27	46.0	1.95	6.6	48.7	6	97
4.54		2.3	9.2		7	110
6.8		3	12.7		9.1	124
9.1		5	21.5		10	140
11.5		6.8	29		12	167
13.8		8	36.5		13.6	213

A-6 soil, having less percentage of Illite content.

3.5. M_R-CBR relationships

Relationships for estimating the resilient modulus of subgrade material have been developed in order to reduce the cost and duration of road construction projects and to make engineer's work easier [21]. Following equations were developed through regression analysis for both the soils that gave the relationship between resilient modulus and CBR of that area specifically.

$$\text{For A-2-6} \quad \text{Soil } M_R \text{ (MPa)} = 18.34 CBR^{0.92} \tag{4}$$

$$\text{For A-6} \quad \text{Soil } M_R \text{ (MPa)} = 3.43 CBR^{1.2} \tag{5}$$

The *t*-test is used to assess whether the mean of the two sets of data with roughly normal distribution are significantly different from one another or not. For this, we conducted a *t*-test statistical analysis with each of the previously developed equations and the results are shown in Table 5. The *t*-test value represents probability of less than 0.05 in most cases which shows that there is a significant difference between mean of the data values due the difference in the mineral composition of the soils. There is no significant difference between the mean values of this research with Green and Hall for A-2-6 soil and Razouki (2014) for A-6 Soil.

To validate the M_R obtained in this investigation, the results of this study were compared to well-known published M_R equations as shown in Figs. 10 and 11. The data was plotted using these equations to assess their validity for our soil type. Razouki [17] over-estimate resilient modulus for A-2-6 soil as shown in Fig. 8. The M_R values obtained in this study for A-2-6 soil show a significant correlation with those reported by Green and Hall [24]. Similarly, The A-6 soil show a significant correlation with those reported by Razouki [18].

The analysis shows that the M_R values calculated using earlier equations differ at the specified CBR. This shows that these equations

Table 5
T-test statistical analysis.

T-test	Razouki (2001)	Razouki (2017)	Green (1975)	Garver (2015)	Heukelom (1962)	TRRL (1984)	Razouki (2014)	Abubakar (2022)
A-2-6 soil	3.21E-06	4.82E-11	0.051397	0.0513709	0.0032044	0.0016	4.65E-06	1.737E-07
A-6 Soil	0.0013	3.6E-14	8.30E-08	0.0009579	0.0014239	0.0005	0.67721	0.001668

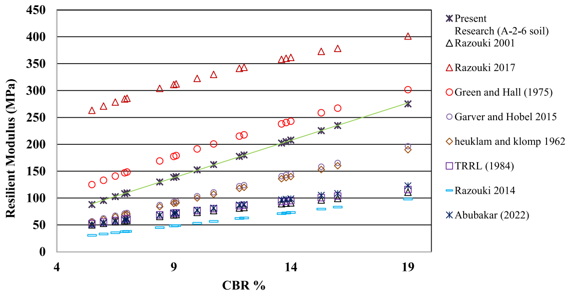

Fig. 10. Comparison of M_R with past researchers (A-2-6).

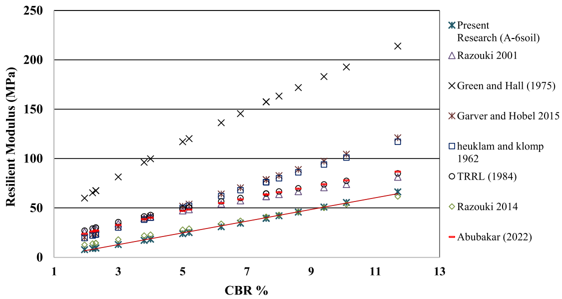

Fig. 11. Comparison of M_R with past researchers (A-6).

cannot be used for each soil type. Every researcher has used their own locally available soil which may have different percentages of mineral composition. Fig. 12 shows the measured M_R values of both soil types plotted against the equation developed by Abubakar [14], which shows that A-6 soil underestimates and A-2-6 soil overestimates the M_R values of subgrade soil.

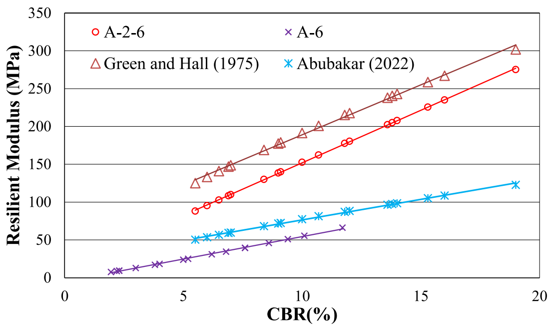

Fig. 12. Comparison of both soil with abubakar.

4. Conclusions

In conclusion, this research will contribute to the new perspective in the relationship of CBR and resilient modulus of the subgrade soil. The region-specific approach is incorporated to determine the resilient modulus. Also, the determination of mineral composition enhances the accuracy of the soil strength parameter i.e M_R. This research has not only enhanced our geotechnical knowledge but is also a practical tool for estimating resilient modulus with more accuracy for the design of projects in Pakistan. The present study concluded that.

- Illite quantity has a significant effect on the CBR and M_R value. Higher the Illite quantity leads to the higher CBR & M_R value due to its contribution to cohesion and bearing capacity of soil but when montmorillonite quantity increases, it reduces CBR and M_R even at higher Illite quantity value due to its higher swelling and expansive characteristic.
- The CBR strength ratio of both the soils showed an increase with increasing surcharge weight and Illite content. A higher increase in CBR strength ratio was observed for A-6 soil compared to that of A-2-6 soil with same increase in surcharge weight, indicating that surcharge weight has more prominent effect on fine-grained soils than that of coarse-grained soil. CBR increased up to 4 times for A-2-6 and 1.5 times for A-6 soil at 13.8 kg surcharge load.
- Compression velocity both for A-2-6 & A-6 soils increased significantly with an increase in surcharge weight to 13.8 kg, resulting in an increase in the M_R value of both the soils. M_R value obtained through ultrasonic pulse velocity for A-2-6 & A-6 soil showed a close relationship with the equations developed by Abubakar [14], suggesting a conservative approach. A-2-6 soil is strongly correlated with the equation developed by Green and Hall i.e $M_R = 37.3CBR^{0.71}$ and A-6 soil is strongly correlated with the equation developed by Razouki i.e $M_R = 5.005CBR+2.9173$.

Recommendations

The study suggests broadening its scope by including diverse soil types and exploring additional resilient modulus assessment methods. It recommends investigating the influence of climate on the relationship between Illite content and soil properties. The integration of advanced technologies like remote sensing is proposed for more accurate large-scale soil assessments. Additionally, exploring further Illite-related parameters, such as particle size distribution, is recommended to deepen the understanding of observed correlations in subgrade soil properties.

Data availability

- No, the data has not been deposited into a publicly available repository.
- Data will be made available on request.

CRediT authorship contribution statement

Kashif Riaz: Writing – review & editing, Writing – original draft, Methodology. **Naveed Ahmad:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests Kashif Riaz reports financial support and article publishing charges were provided by A & Z Contractors and Sir Zaheer Academy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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