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Mineralogy as a Key Paremeter for Strength Evaluation of Clayey Subgrades

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Abstract- The current pavement design practices do not take into consideration the mineralogy of clays. The major task of this research was to study the effect of clay content on strength characteristics of soils belonging to same group i.e., A-4, as classified by American Association of State Highway and Transportation Officials (ASHTO). Samples were collected from three different areas of Punjab. Various classification, compaction and strength tests as required for pavement subgrades were performed following American Society for Testing Materials (ASTM) standards. X-Ray diffraction analysis was also performed to support data obtained from hydrometer analysis for determination of clay content. It was observed that clay content has a major role in controlling index properties, swelling potential and strength characteristics for fine-grained soils. With increase in clay content, plasticity index and swelling potential of the soil were increased, while a decrease was observed in soaked and unsoaked California Bearing Ratio (CBR) values. Hence mineralogy should also be given due importance while selecting subgrade soil.

Keywords- Mineralogy, Clay, Subgrade, California Bearing Ratio, A-4 Soil

I. INTRODUCTION

Compressible soils and expansive soils change their volume rapidly when they come in contact with water. Swelling of soil depends on the availability of water and type of minerals present in soil. Based on the chemistry, all minerals exhibit different swell level. Maximum swell is found in Montmorillonitic soils. Illites have very low potential for swelling. Clay minerals should be identified to have an estimate of swelling potential of soil at site. Fabric of soil has also effect on the swell of soil. Therefore, identification of materials responsible for swelling is very important.

The soils encountered in Kohat Cantt possess high volume change upon wetting due to which various buildings and roads have been badly damaged. Most of the damaged buildings and roads had to be reconstructed. Figure. 1(a) and 1(b) below show damages caused to buildings and roads in Kohat Cantt respectively.

Fig. 1: Damaged structures in Kohat Cantt
(a) Building and (b) Road

Reference [1] carried out a study in Arizona State University. In his research he selected soil samples from Colorado, Texas and Arizona and identified the minerals present in the soils with the help of X-Ray Diffraction testing (XRD). Meanwhile, different swelling tests were also carried out in laboratory on the soil samples. The swelling results from the laboratory tests and literature available were compared to find out which minerals were significant to swelling soils. It was observed that the soils containing more amounts of Smectite minerals showed more swelling with increase in moisture. The amount of gypsum present in the soil was also significant to the swelling behavior of soil. Therefore, it was recommended to consider the amount of Smectite minerals and gypsum in the design of structures being constructed on expansive soils [1]. Reference [2] carried out a study on Low Plastic Clayey Soil (CL) having optimum moisture content of 12% and Maximum Dry Density of 21 KN/m^3. California Bearing Ratio (CBR) of the soil samples prepared at optimum moisture content were taken after different period of soaking. Values of CBR were taken after 0, 12, 24, 36, 48, 60, 72, 84 and 96 hours. It was observed that value of CBR decreases quickly with time of soaking up to 24 hours. After that value of CBR decreases quite slowly. Samples for the moisture content were taken from top, bottom, and middle layers of the specimens. It was also observed that with longer soaking period, moisture content in upper layer was more as compared to that of bottom layer [2].

Reference [3] conducted a study to determine the relationship between moisture content and sub grade strength. Nine (9) different soil samples were used in this research. With the help of modified proctor test, optimum moisture content and maximum dry density of soil samples were calculated. Thereafter, California Bearing Ratio test was performed on un-soaked soil samples, after 1-day, 2-day, 3-day and 4-day soaking. The results showed that with increasing number of days of soaking, CBR decreases due to entrance of water. It was observed that a drastic decrease in value of CBR occurs from un-soaked to 1-day soaking condition. With further increase in soaking period, CBR decreases gradually. The moisture contents of all samples were observed with each day of soaking. It was observed that maximum water enters from un-soaked condition to 1 day soaking, which was main cause of drastic decrease in CBR value. After that the rate of entrance of water decreases because soil is closing towards saturation [3].

Reference [4] carried out a study to determine the effect of clay fraction on the strength of dry and remoulded soils. In the study strength of eight different soil samples from Australia having different type of clay, mineralogy, particle size and amount of clay were compared. It was observed that strength of soil increased with increasing the clay content. It was further observed that the soils having clay content more than 20%, there was major increase in strength soil. Further correlations between types of clays, particle size and cation exchange capacity showed that sensitivity of the strength was greatest in soils having more amount of smectities followed by Illites and Kaolinites [4].

Reference [5] carried out a study on comparison of CBR values obtained from Laboratory Tests and Dynamic Cone Penetration (DCP) test. He used three different soils, which were classified as CL, ML and SP according to Unified Soil Classification System. When CBR tests were conducted at different values of moisture contents, it was observed that maximum value of Un-Soaked CBR comes at optimum moisture content. The major task of this research is to study the soils of same type, i.e., A-4 (AASHTO classification) but having different quantities of clay minerals, so the behavior of different quantities of clay minerals on the strength properties of same soil type can be accessed. The current design practices in Pakistan do not take into consideration the mineralogy of clays. It was also recommended by [6] that current standards should be revised and should take into consideration the clay mineralogy. It has been observed that the major damage is caused by expansive soils. Expansive soil creates problems due to the interaction of minerals having clayey nature. These minerals produce swelling and shrinkage problems [7]. The high value of plasticity, swell potential, and shrinkage are some of the major damage-causing features of expansive soils. For road projects, the pavement may undergo cracking due to the uneven heave or damage due to the swelling and shrinkage behavior of expansive soil when it contracts with water [8]. Shrinkage and swelling of expansive soil cause more than 50% of soil-related damages to the infrastructures worldwide [9]. Experts are of the view that most of damage caused to the structures is not due to poor design, but the major reason is failure of engineers to identify the troublesome soils at the start of work. Hence, if we know the composition of different minerals present in the soil at site, we can have an idea about the post construction behavior of soils. Therefore, it is imperative to design a geotechnical scheme which will consider both. If this information is available, structures constructed will perform their function in a better way. The major objective and scope of the project were as follows:

1. To determine minerology of A-4 soil samples collected from different locations.
2. To study the effect of mineralogy on CBR (un-soaked and soaked) of A-4 soils.
3. To study the effect of mineralogy on swelling potential of A-4 soils.

II. MATERIALS AND METHODS

2.1 Soil

For studying the effect of clay content on the strength properties of subgrade soils, soils samples were collected from three different sources. Samples collected from Kohat, Islamabad and Faisalabad were referred as Soil-A, Soil-B and Soil-C, respectively. Soil samples were collected from the site located for the collection of subgrade material of roads locally. These soils were mostly used by the local construction industry for the preparation of subgrade.

2.2 Soil Classification

The soil samples were classified as per AASHTO soil classification system. Grain size distribution and index properties (liquid limit, plastic limit and plasticity index) were determined for the classification of three soil samples.

2.2.1 Grain size distribution

Gradation curves for soils A, B and C are shown in Figure. 2. Which show a high percentage of finer particles in all soil samples. Soil A, B and C contain 84%, 80% and 81% finer particles respectively.

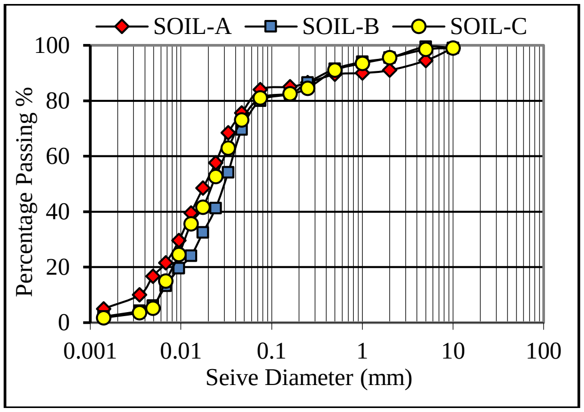

Fig. 2: Grain size Distribution Curves (GSDC)

2.2.2 Atterberg Limits

The liquid limit, Plastic Limit, and Plasticity Index of both soil samples were determined in the laboratory according to ASTM D4318. Material passing through sieve no 40 was used for the test. The soil's plasticity can be measured through the plasticity index of soil. Plasticity index can be obtained through numerical difference of liquid limit and plastic limit, i.e. (P.I = L.L - P. L). Results of Liquid limit tests of soil A, B and C are shown in Figure. 3.

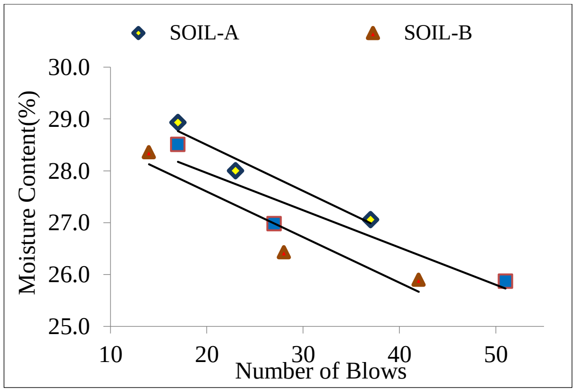

Fig. 3: Flow curves for soil samples

On the basis of results obtained from grain size distribution and Atterberg's limit, all three soil samples were classified as A-4 soil as per AASHTO soil classification system as shown in Table I.

Table I: Plasticity Characteristics of Soil Samples

Soil	**Liquid Limit**	**Plastic Limit**	**Plasticity Index**	**Classification (AASHTO)**
A	28.10	19.77	8.33	A-4
B	27.70	20.52	7.18	A-4
C	27.25	21.50	5.75	A-4

2.3 Hydrometer and XRD Analysis:

To determine the percentage of fine clay particles passing sieve number # 200, hydrometer analysis (ASTM D-422) was performed. X-Ray Diffraction analysis (XRD) was also performed to determine chemical composition of soil samples, Results of these tests are discussed in next section.

2.4 Modified proctor test

Maximum Dry Density (MDD) of all soil samples were determined with the help of modified proctor test. Four samples of each soil were prepared with moisture contents ranging from 3.3% to 15% for soil A, 4 to 16% for soil B and 4 to 15% for soil C. The soil samples were compacted in five layers in a 150 mm diameter mold with 25 blows of 4.5 kg hammer per layer. The dry density and moisture content for each trial were determined to find out Maximum Dry Density (MDD) and Optimum Moisture Content (OMC).

2.5 California Bearing Ratio Test (CBR)

The potential of any material to be suitable for usage as subgrade material is determined by CBR test. Unsoaked and Soaked CBR tests were performed on all three soil samples. For each specimen, three moulds were prepared with 10, 30, and 65 blows and CBR values were calculated against 95% (MDD). CBR tests were carried out according to AASHTO T-193. Soaked samples were placed in the water for 96 hours at room temperature.

2.6 Swelling Potential

The swelling potential of A-4 soil samples was determined according to AASHTO T-193, samples were soaked for 96 hours and swelling potential was determined with dial gauges. Swell potential of all CBR samples prepared with 10, 30 and 65 blows respectively is presented in the next section.

III. RESULTS AND DISCUSSION

Results of the tests performed on the soil samples are presented in this section.

3.1 XRD Results

Results of XRD test showed that all the soil samples contained similar minerals but had different percentages by weight. Out of the minerals identified, only Dickite and Muscovite were clay minerals belonging to Kaolinite and Illite-Mica group, respectively. Whereas Albite, Quartz and Calcite Magnesium were non-clay minerals. So, the percentage of clay minerals obtained in soils A, B & C was 19%, 5% & 4%, respectively. Meanwhile, X-Ray Diffraction Analysis of the soil samples were also carried out to calculate the type and percentage of clay minerals present in soil samples. The results of the XRD test are shown in Table II.

Table II: Percentages of Clay Minerals as Determined *by XRD Test*

Sample Name	**Identified Minerals**
Soil-A	Albite 40%, Quartz 23%, Calcite Magnesium 18%, Dickite 13%, Muscovite 6%
Soil-B	Quartz 40%, Albite 29%, Calcite Magnesium 26%, Dickite 5%
Soil-C	Quartz 52%, Albite 32%, Calcite Magnesium 12%, Dickite 4%

3.2 Hydrometer Analysis

Results of the Hydrometer analysis of the soil samples are presented in Fig. 4. The results showed that soil samples had different clay contents, with Soil-A having maximum amount of clay sized particles and Soil-C having least amount of clay particles. The soils were basically silty clays belonging to the group of A-4 soils according to the AASHTO soil classification system.

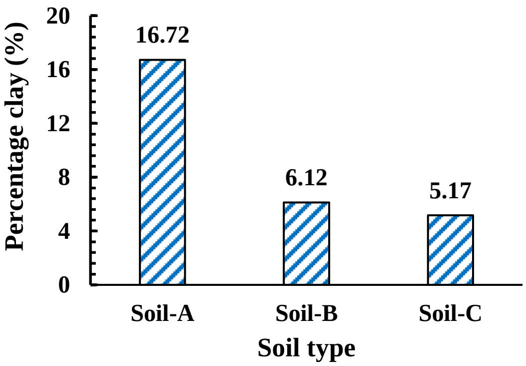

Fig. 4: Clay percentages as determined by hydrometer analysis

3.3 Comparative analysis of Hydrometer and XRD test results

Percentage of clay obtained by Hydrometer Analysis (ASTM D-422) was compared with that obtained by XRD Analysis. It can be observed from Fig. 5 that in all soil samples, there is a difference in quantity of clay minerals calculated by XRD and Hydrometer analysis. This difference in clay percentage by two methods may be due to the reason that only 3-5 gram of soil sample is used for XRD testing, which may not give a true representation of soil. So, the amount of clay minerals calculated by Hydrometer Analysis was used during the study.

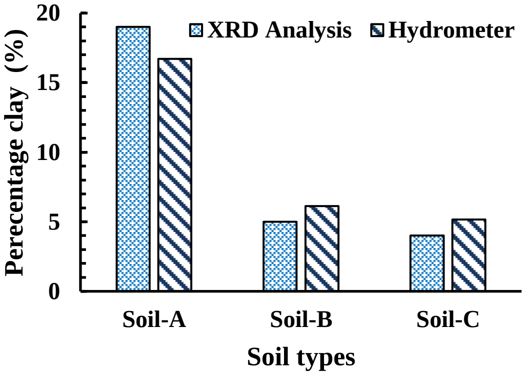

Fig. 5: Clay percentage comparison

3.4 Modified Proctor Test

Modified Proctor test (AASHTO T-180B) was performed on soil samples and Optimum Moisture Content & Maximum Dry Density of soil samples were calculated. (MDD) and OMC of soil A, B and C are shown in Fig. 6. For soil-A, Optimum Moisture Content was calculated to be 11.9% and Maximum Dry Unit Weight is 19.30 kN/m^3. For soil-B, Optimum Moisture Content was calculated to be 11.7% and Maximum Dry Unit Weight is 19.40 kN/m^3. For soil-C, Optimum Moisture Content was calculated to be 11.2% and Maximum Dry Unit Weight is 19.85 kN/m^3.

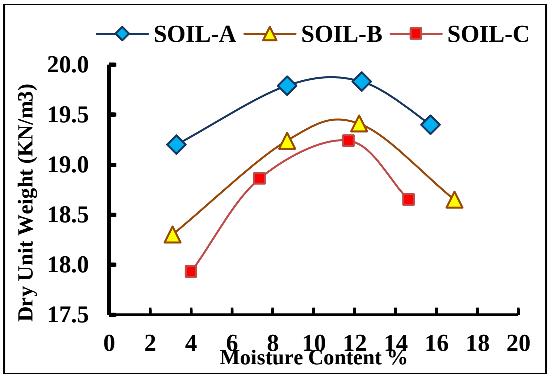

Fig. 6: Compaction curves of soil samples

The OMC and MDD values determined for different soil sample are shown in Fig. 7. A slight drop in MDD and rise in OMC has been observed with increase in clay content.

Reference [10] has noticed a similar variation during his study on residual soils and correlated it with plasticity index of soil samples.

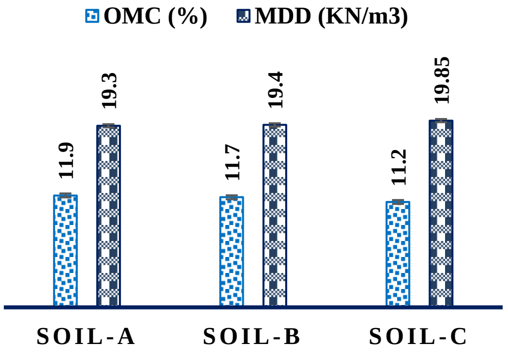

Fig. 7: MDD and OMC variation with soil types

3.5 California Bearing Ratio Tests

3.5.1 Unsoaked CBR

Results of the unsoaked CBR test of soil-A, B and C are shown in Fig. 8. A significant increase in the CBR value of soils is observed with decrease in the clay content. Effect of the compaction on the soil samples can also be seen. The value of CBR increased from 2.3 to 8.1%, 4.7 to 9.9% and 7.4 to 13% for 10, 30 and 65 blows compacted samples, respectively. The clay content was maximum (16.72%) in soil-A among the three samples tested and it has the lowest value of CBR.

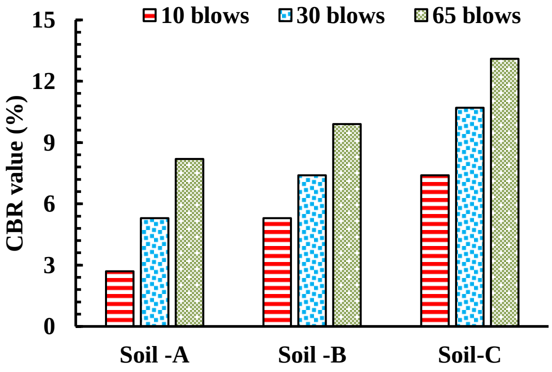

Fig. 8: Unsoaked CBR value of all soil samples

3.5.2 Soaked CBR

Results of soaked CBR tests of soil-A, B and C are shown in Fig. 9. Samples were soaked for 96 hours to simulate the worst possible condition that may occur during the lifetime of pavement subgrade material. The CBR value of subgrade soils being soaked for 96 hours is always less than the Unsoaked CBR value in untreated or natural state. It is because of the adverse effect of water in which soil sample is soaked for 96 hours which cause swelling and over-consolidation in the soil. Results of soaked CBR were same in the trend as of the Unsoaked CBR test but the values were comparatively less than those of Unsoaked CBR values. The value of CBR increased from 1.4 to 6.8%, 3.2 to 8.4% and 5.3 to 10.4% for 10, 30 and 65 blows compacted samples, respectively.

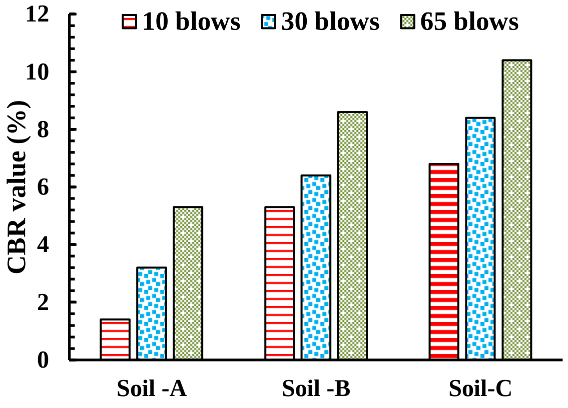

Fig. 9: Soaked CBR value of all soil samples

The increase in CBR value is attributed to the plasticity index and maximum dry density of soil which were directly related to the percentage of clay particles. The CBR value decreased with increase in plasticity index of soil. Also, CBR value increased with maximum dry density. As maximum dry density of soil increased, CBR values also increased, which indicated a linear relationship between these two parameters as previously reported by [11].

3.5.3 CBR at 95% (MDD)

Fig. 10 presents a comparative analysis of the effect of clay minerals percentage on the unsoaked and soaked CBR values. CBR values are obtained at 95% MDD to attain the required moisture content at the site during compaction of the subgrade material. Comparison of soaked and unsoaked CBR of all three soil samples followed the same trend as discussed above. The values of CBR increased with the decrease in clay content of soil samples. These results showed that there was a correlation between CBR and clay content of the soil. As the clay content is increased or decreased, it directly affected the CBR value. Also, the drop of CBR from unsoaked to soaked condition was found maximum for soil having maximum clay content. From the comparison made in graphical analysis of data, it could be concluded that for soil with low clay content, the ratio of unsoaked/soak CBR= 0.3 (approximately). Similar trend was observed by [12] by conducting experiments on alluvium soils.

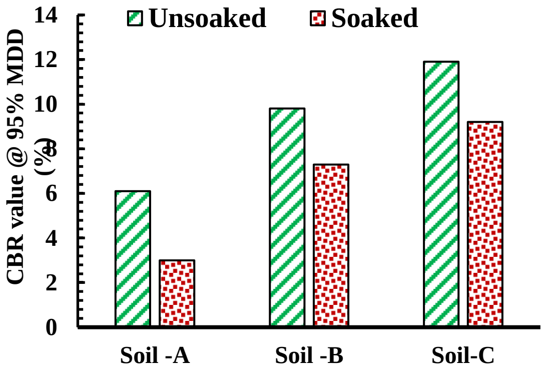

Fig. 10: Comparison of unsoaked and Soaked CBR values at 95% of MDD

Reference [13] has reported the effect of clay mineral type on undrained strength of soil. Because CBR is a measure for soil strength, the correlation between mineralogy and CBR with plasticity characteristics is reasonable. Further, CBR reduced as water content rised (i.e., plasticity limits), which was not surprising, given that soil strength dropped in a nonlinear manner as water content was increased as reported previously by [14]. The results also showed that CBR had a stronger relationship with plastic limit than liquid limit or plasticity index for both soil types and similar effect was observed by [15].

3.6 Swell potential

The swelling potential for all the soil samples is shown in Fig. 11. The effect of compaction effort on the compacted soil samples can be seen in the swell potential results. The higher values of swelling percentage showed the expansive nature of soil. The soil-A with maximum percentage of clay content showed maximum swelling potential. The cohesive nature of the clay particles allowed the soil to swell and the extent of that cohesion between the soil particle increased due to increase in clay content. The increase in the finer clay particles increased the surface area and thus the water holding capacity was also increased, resulting in more swelling of the fine clay particles. As the clay content decreased, the swell was also reduced. Clay particles generally absorb more water due to higher surface area. Soil-A contained more percentage of clay minerals. As a result, with the increase in moisture content, interparticle friction and internal cohesion between the particles decreased and they started to move rapidly. Reference [16] carried out a study on various types of soils and identifed that the soils having less than 10% expansoin had low probibility for swelling. As all these soils had less than 10% expansion, so their swelling potential was very low. It can be observed from results that maximum amount of swelling occurred in Soil-A (having 16.72% clay minerlas).

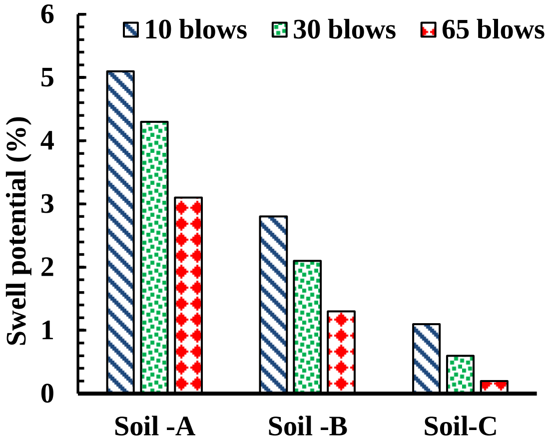

Fig. 11: Swelling potential for different soils against different compaction efforts

One the other hand, the acceptable swell percentage value allowed for subgrade material is 0.3% as per standards of National Highway Authority Pakistan [17]. With the decrease in the clay content, the soil observed improvements in swelling resistance, and ultimately, it satisfied the criteria of acceptability limits of 0.3%. It can also be explained by the fact that initially weight of soil was more, and weight of water was less. As the moisture content of soil increased, percentage of soil solids started decreasing. As soil swelled, with reduction in percentage of soil at high moisture, rate of swelling was decreased. It was also observed that maximum swelling occurred in Soil-A, as it contained maximum quantity of clay particles.

3.7 Relationship of clay mineral quantity with CBR (Un-Soaked & Soaked conditions) and swelling potential

X-Ray Diffraction analysis indicated that the soils used in this study contained the clay minerals belonging to Kaolinite and llite-Mica Group; however, they were present in different quantities for different soil types. Soils-A, B & C contained 16.72%, 6.12% & 5.17% clay minerals, respectively. According to the General Specifications of National Highway Authority (NHA), the soil being used for subgrade should not have Soaked CBR value less than 5% and the swelling percentage should be less than 0.3%. As the soils being used for this study have more than 5% Soaked CBR, (Soil-A), it is not suitable for using as subgrade material.

IV. CONCLUSIONS

After determining index properties, compaction characteristic, CBR values and percent swelling of various soils (A, B & C), following conclusions have been made:

1) A-4 soil samples collected from different localities showed different mineralogical composition and plasticity characteristics.
2) Both soaked and unsoaked CBR values were decreased with increasing clay content.
3) For same clay content, soaked CBR value was lower than the unsoaked one. This difference was maximum for the soil with higher clay content.
4) Swelling potential of soil was increased with increasing clay content.

The current research reveals the importance of soil mineralogy on strength and swelling potential of soil. It shows that mineralogy should also be given due importance while selecting soil for a project.

The research was conducted using limited number of A-4 soil samples only. There is a need to expand this work to other soil types with different mineralogical compositions to get a better insight about role of mineralogy on soil behavior.

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