



Appraisal of Bearing Capacity and Modulus of Subgrade Reaction of Refilled Soils

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Abstract

Soil is remoulded, replaced, or improved in place to meet the required engineering properties. Relative compaction is the measure of the resulting engineering improvement. But design engineers need the allowable bearing capacity while the modulus of subgrade reaction is the primary input of modern foundation design software. The current research appraised a correlation between Relative Compaction (RC), Moisture Content (MC), and allowable bearing capacity (q_{all}) and another correlation between q_{all} , RC , MC , and modulus of subgrade reaction (K_s). The test samples were extracted from each trial of the standard proctor test using purpose-built extraction tubes. Allowable bearing capacity has been determined by performing unconfined compression tests on the extracted tubes. The relationships have been established employing statistical analysis. It was noticed that soil samples at the lower moisture content (6-9%) show brittle failure before reaching the allowable strain. The soil samples having a moisture content of 10-14% exhibited shear failure, nearly simultaneous to the allowable strain. The soil samples having higher moisture content undergone a strain of 15% without showing the shear failure. A simple equation has also been appraised to determine K_s involving the three-input variable, i.e., MC , RC , and q_{all} . Moderate correlations have been found to exist between the studied parameters, owing to some other variables' influence. Recommendations for future studies have been drawn to quantify the effect of identified parameters.

Keywords: Relative Compaction; Modulus of Subgrade Reaction; Optimum Moisture Content; Y-K Relation; Y- Bearing Capacity Relation; Failure Modes.

1. Introduction

The migration of population towards cities due to the lack of basic facilities in the rural areas of developing countries exerts extraordinary pressure on the recipient cities' infrastructure. Due to the multiplying growth of the population, agriculture and barren lands are converted into residential and commercial entities. The barren lands in the vicinity of Islamabad, Pakistan, and Pothohar Plateau have badland topography. There are valleys as deep as 10 m. The topography is being altered to convert these lands into residential units. The uncontrolled filling of 8-12 m depth has been observed in these newly developed housing schemes during the author's fieldwork in this region. The settlement of buildings and roads has become a norm in these developing lands. The compaction of the subgrade is the most recommended and feasible technique for soil improvement. Generally, compaction increases the soil density, enhances its strength, and reduces its compressibility and permeability. This modification's ultimate result is a

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significant increase in subgrade bearing capacity, minimizing the detrimental effects of a volumetric change (e.g., frost heave, swelling, shrinkage), and control of water flow (e.g., seepage, subsurface contaminant transport).

Geotechnical consultants so often recommend subgrade compaction or provision of gravel cushion under the foundations having a shallow water table. The quantification of the soil improvement through compaction remains unanswered. So often, the question arises that for the relative compaction of 95% or 98% (as specified in the specifications) of refilled material, what is associated allowable bearing capacity/modulus of subgrade reaction of the improved/compacted soil? The current study aims to fill the literature gap associated with refilled and re-compacted soils' bearing capacity. The research work aimed to quantify this improvement and work out the relationship between relative compaction and bearing capacity of the fine-grained soils.

Further to relative compaction and q_{all} relationship, a relationship between relative compaction and modulus of subgrade reaction (K_s) has also been established. K_s is the primary input for most of the modern foundation design software. The extraction of samples from the Moulds prepared using standard proctor procedure is the novel methodology. This methodology ensures the uniform composition and quality of samples used for relative compaction and unconfined compression tests, eliminating the sampling-induced variations in the results. The paper is presented in five sections. Literature reviews (Section 2) on the subject follow the introduction section. Section 3 describes the methodology of research; Interpretation, analysis, and discussion of results have been presented in Section 4. Section 5 presents the conclusions drawn from the study.

2. Literature Review

The major physical properties which control the allowable bearing capacity of soils are relative compaction, moisture content, and particle size distribution. Models that use empirical correlations for both cohesive and non-cohesive soils relate Optimum Moisture Content (OMC) and maximum dry density or unit weight to soils' physical or index properties, such as the Atterberg index (liquid limit, LL, and plastic limit, PL), the specific gravity of solids (G_s), and the grain-size distribution. Davidson evaluated the relationship between relative density and plasticity index [1]. The relationship of compaction characteristics with basic soil properties can be used to validate the test results. These relationships can also be useful for preliminary estimations for the projects involving bulk earthwork activities [2]. Compaction is the process to remove air voids from the soil by using mechanical force. It results in a reduced post-construction settlement, reduced permeability, and increases bearing capacity/modulus of subgrade reaction of soils. The study by Sridharan et al. questioned the accuracy of compaction characteristics using only the soils' liquid limit [3]. Research work on relative density and various index or mechanical properties of soil is summarized as follows, prediction of $Y - MC$ relationships [4], Compaction-Permeability prediction [5], the relationship between compaction parameters and Atterberg's limits [6], Y_{dmax} and soil gradation [7], estimation of optimum moisture content and maximum dry density [8, 9], the effect of degree of saturation on Y_{dmax} [10] plastic limit and compaction characteristics [11, 12], Unsaturated shear strength and percentage of low plastic fines [13]. An empirical correlation between moisture content and CPT resistance for preliminary estimation of tip resistance [14].

Li and Sego (2000) Determined the $MC - Y_d$ relationship separately for the Dry of Optimum (DOP) and the Wet of Optimum (WOP) based on the LL and the G_s for each soil and further derived an equation with both soil and compaction effort parameters to predict the complete compaction curves of fine-grained soils [15]. Different types of fill and the selection of the appropriate laboratory maximum dry density for each fill type has been discussed by Al-Badran and Tom (2014) [16]. A comparison of the undisturbed and refilled clays' strength characteristics has been appraised by Khemissa et al. (2018) [17]. Soil Classification has also been correlated with permeability, MDD, and OMC [18]. The potential of saw as an admixture for soil improvement has been evaluated and reported to be ineffective without the addition of any adhesive [19]. Basic testing and mathematical expressions related to soil improvement using explosives have been reported by Lalić (2006) [20]. These correlations are further related to the liquid limit of soil in the same study. A mathematical model has been proposed to determine the settlement of shallow foundations by Kristić et al. [21]. For compacted fine-grained soil, the shear strength at the plastic limit ranges from 150 to 250 kPa, as reported by ASTM D4318 [22]. Hamdani developed a procedure to find maximum dry density and optimum moisture content of soil using only one trial test using 9 % moisture content [23]. The effect of confinement and cement content on the resulting bearing capacity of aeolian sand has been reported by Lopez-Querol (2017) [24]. A strong correlation between plasticity characteristics and compaction has been reported by Day et al. (2000) [25] in terms of compression index, shrinkage index, shrinkage limit, and liquid limit of soils, refer to Equation 1:

$$IS = LL - SL \quad (1)$$

Where; SL is the shrinkage limit, IS shrinkage index, and LL is the liquid limit. Another equation that relates Y_{dmax} with the plastic limit of soil has been proposed by Sridharan and Nagaraj [26]:

$$Y_{dmax} = 0.23(93.3 - wP) \quad (2)$$

Where; Y_{dmax} is the maximum dry unit weight in kN/m^3 , and wP is the plastic limit in percent.

The compaction control criteria are intimately coupled with a strong relationship describing compacted soil's strength in terms of its water content [27]. Joslein presented typical water-density curves known as Ohio's curves and published by the American Society of Testing Materials [28]. An approximation for the shear strength of compacted soils has been reported by ASTM D 4318, and the reported range is 150 kPa to 250 kPa [29]. Plate load tests on a reclaimed site in Egypt, along with dynamic cone penetration tests, have been employed to determine a correlation to estimate deformation modulus of gravelly soils [30].

Standard penetration resistance (N) also correlates well with soil's in-place density [31]. The input variable, i.e., SPT, is more costly and tedious compared to in-place density. The current study aimed at the determination of modulus of subgrade reaction (K_s) using the lab. Density (Standard Proctor). The spatial density of granular soils resulting from the compaction process has been studied by Xia (2014) [32]. The outcome describes it as critical for geotechnical and pavement applications. It is also reported that cohesive strength increases due to aging or curing of soils as determined from the rupture values [33]. The properties and typical behavior of compacted clays have been reviewed and appraised by Kodikara et al. (2018) [34]. Soil composition also affects the soil's resulting compaction, which proposes normalization of OMC and compaction energy [35]. The regression analysis has also been used to develop relationships between UCS and MDD [36]. Compaction control is often the most significant factor affecting the behavior of earthwork projects constructed with compacted, fine-grained soil. Pandian et al. developed a model that enables determination of the density and water content relationship of fine-grained soils separately for the dry and the wet sides of optimum based on the liquid limit and specific gravity [37] But this study also leaves the resulting improvement in bearing capacity of soil unanswered.

S. Horpibulsuk et al. have reported that the engineering properties are the function of the physical properties of compacted soils. They have further derived a relationship between the relative density of 90-100% and CBR incorporating Ohio's and modified Ohio's curves for different soil types [11, 38, 39]. Estimation of q_{all} or K_s from the RC has not been appraised in the presented literature. This study aims to find a correlation between the relative compaction (RC), q_{all} , and K_s for fine-grained soils. It is the most bothering gap in-field operation to estimate q_{all} from the relative compaction of refilled soils. A major factor resulting in poor quality fills and resulting litigations is the improper maximum lab density [40]. Hence, it is of extreme importance to estimate maximum dry density (MDD) accurately, whether determined directly or indirectly.

Regression analysis is normally used to create a mathematical model that can predict a dependent variable's values based upon an independent variable's values—the current study utilized data analysis tools, which is an additional set of tools in Microsoft excel. The multiple regression analysis was performed using the said “data analysis tool” to establish the target correlations.

3. Materials and Methods

3.1. Description of Materials

The samples collected from the Photohar plateau were oven-dried and prepared for re-moulding at varying densities and moisture contents. The samples collected from various sites are well spread over the research area. The collected samples were air-dried and processed. The description of the soil samples used in the tests is low plastic, inorganic clay, and low plastic Inorganic clay with sand. For the samples used in this study percentage passing of #200 sieve ranges from 72.70 to 96.40 %, the liquid limit was in the range of 25.54 to 33.63 % while the plasticity index ranged from 7.91 to 16.09. The soil samples belong to CL groups as defined by the Engineering Classification of Soil. Most of the subgrade soils fall in fine-grained soils as per the Unified Soil Classification System (USCS) in the study area. This evidence is the outcome of the author's geotechnical mapping in the primary component of this research project. Although gradation is considered less significant for fine grained soil as compared to coarse-grained soils. However, the author performed the gradation of the samples by combining the sieve analysis and hydrometer analysis results. The soils' gradation differs slightly. Figure 1 presents the upper bound and lower bound gradation curves for the soil samples used in the current study. The gradation curves of all the other samples lie in between these two curves.

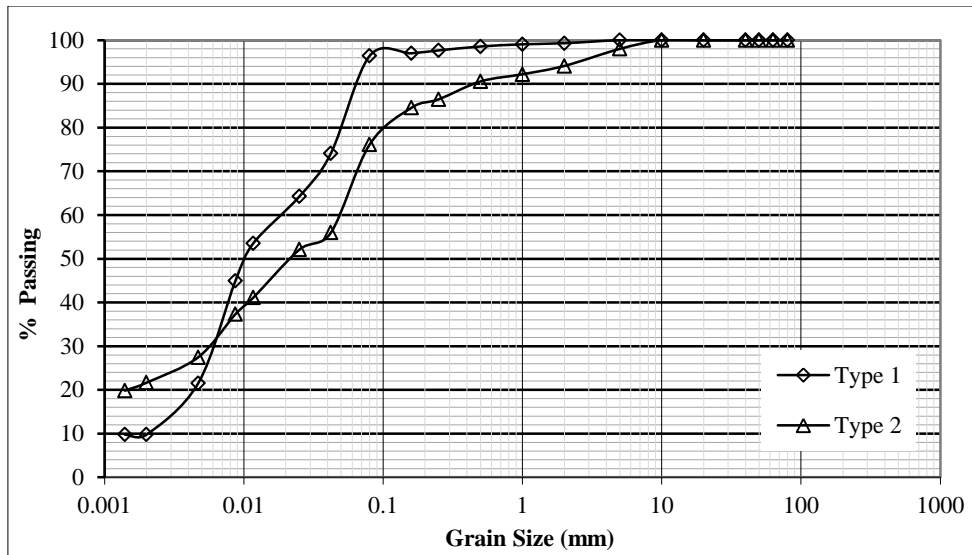


Figure 1. Grading Curves of Samples

3.2. Testing Procedures

The compaction procedure used was comparable with the standard proctor test as per (ASTM D698). The process also included the recovery of three cylindrical samples from each trial using a purpose-built apparatus shown in Figure 2.



Figure 2. Purpose Built Extraction Tubes

The methodology's novelty is the extraction of samples for unconfined compression tests from the Moulds prepared according to the standard proctor method, ensuring the consistent quality and state of samples used for both of the comparative tests. This methodology also enables the user to compare the results with famous Ohio's compaction curves. The test started with the addition of 6 % water to the air-dried samples. The study did not use lower moisture content, considering the site conditions, rarely showing less than 6% moisture content for fine-grained soils. Secondly, the compaction specifications rarely require a relative density of soil less than 85% of the maximum standard proctor dry density. (Lower moisture results in relative density less the 85% of the maximum Lab. density).

Three purpose-built Shelby tubes of 38 mm diameter and 80 mm length were penetrated in the moulded soil. These tubes were extracted from the proctor mould using a sample extruder, and soil samples were recovered from these tubes using a sample extruder. The tubes were trimmed to the size of 38 mm and Ø76 mm length to meet the requirement of ASTM D2166. The performance of unconfined compression tests confirms ASTM D2166 procedures. The unconfined compressive strength tests performed using a testing machine installed with a loading ring of 150 kN capacity; the strain gauge of 0.001 mm least count was installed in the load cell to measure the load cell's deflection. The measured deflection of the load cells was converted to the corresponding load using the calibration chart of the load cell. The strain in the sample was measured simultaneously using the deflection gauge at the bottom of the sample. The least count of the deflection gauge was 0.01 mm. The load increased using acceleration to produce approximately 1.75% strain per minute. Time intervals were measure using the stopwatch for the pre-decided strain gauge reading. Figure 3 shows the graph between time and corresponding strain.

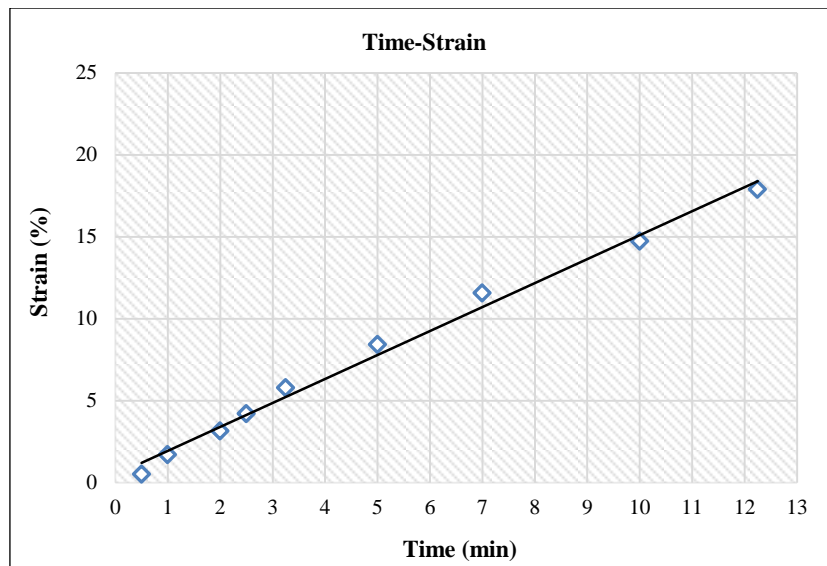


Figure 3. Strain Vs. Time Chart

Triplicate samples for unconfined compressive strength were tested to delineate the change/improvement in unit weight, q_{all} , and modulus of subgrade reaction (K) with increasing moisture content. Figure 4 presents the schematic diagram showing the step by step procedure of the research methodology.

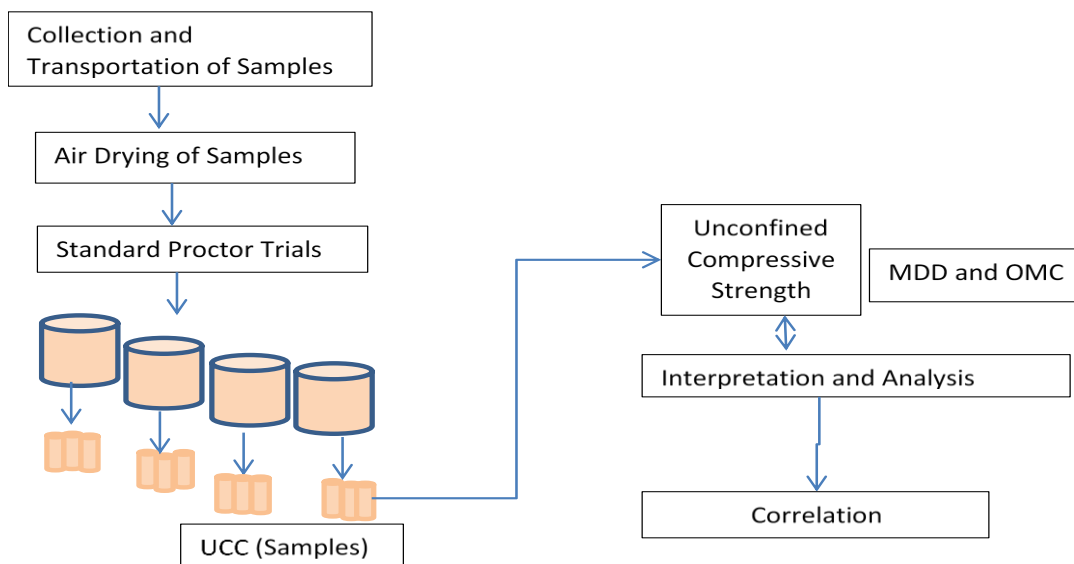


Figure 4. Schematic diagram of research methodology

This study performed a total number of 120 unconfined compressive tests with varying moisture content and densities, and one hundred and 162 moisture content tests along with 42 standard proctor trials. The schematic distribution of tests performed is summarized in Table 1.

Table 1. Description of Tests Performed

Sr. No.	Test Description	No. of Test(s)	Standard Designation
1	Standard Proctor Test	10	ASTM D 698
2	Unconfined Compressive Strength	120	ASTM D 2166
3	Sieve Analysis	20	ASTM D 6913
4	Hydrometer Analysis	20	ASTM D 7928
5	Liquid Limit	20	ASTM D 4318
6	Plastic Limit	20	ASTM D 2487
7	Soil Classification	20	ASTM D 2487
8	Moisture Content	120+42	ASTM D 22 16

4. Results and Discussion

The Optimum Moisture Content (OMC) ranges from 11.77 to 15.62%, and maximum dry density Y_{dmax} ranges from 1823.2 to 1930.3 kg/m³ for the soils under evaluation. Table 2 shows the detailed results of sieve analysis, hydrometer analysis, Atterberg’s limits, soil classification, and standard proctor tests.

Table 2. Outlines of Soil Parameters

Sieve Size	Unit	Soil Source									
		1	2	3	4	5	6	7	8	9	10
Percentage Passing (%)											
10	mm	100	100	100	100	100	100	100	100	100	100
5	“	96.85	95.20	95.35	98.00	98.00	97.75	100	100	100	99.45
2	“	96.60	90.75	92.85	94.10	91.90	97.05	97.40	99.55	99.30	98.55
1	“	95.75	88.20	91.80	92.20	87.25	96.80	96.40	99.10	99.05	97.95
0.5	“	94.85	86.15	90.65	90.55	83.70	96.60	95.55	98.45	98.55	97.35
0.25	“	94.20	83.70	87.80	86.45	79.35	96.25	92.40	96.15	97.65	95.85
0.16	“	93.50	82.95	85.10	84.55	77.40	96.05	91.25	94.60	97.00	95.20
0.08	“	92.95	81.05	82.20	80.15	72.70	95.80	90.10	92.50	96.40	94.70
LL	No.	33.63	27.93	29.08	25.62	25.54	28.50	26.96	32.61	27.08	30.43
PL	No.	17.54	18.67	19.23	18.23	17.62	20.59	17.24	20.63	16.73	20.63
PI	No.	16.09	9.26	9.85	7.39	7.92	7.91	9.72	11.98	10.35	9.80
CLASS	-	CL	CL	CL	CL	CL	CL	CL	CL	CL	CL
Y_{dmax}	Kg/m ³	1838.5	1874.2	1930.3	1892.6	1920.1	1829.4	1862	1914	1832.4	1823.3
OMC	%	14.24	14.1	12.02	13.19	14.94	15.47	15.62	11.77	13.61	14.89

The maximum density of each soil was determined by plotting moisture density curves for each test. Relative densities achieved for each trial were workout using the simple mathematical procedure. Figures 5 show the compaction curve of the samples.

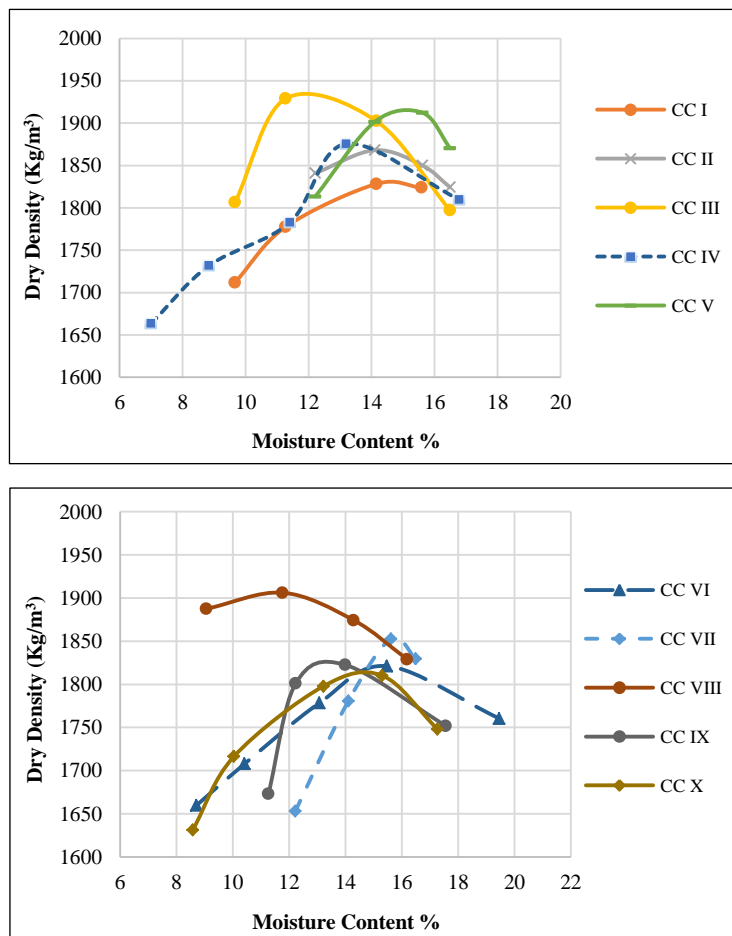


Figure 5. Moisture Density Curves

The samples collected from each trial of the compaction test produced the unconfined compressive strength range of 14.318 N/cm² to 50.112 N/cm². Modulus of subgrade reaction ranges from 8.778 N/cm³ to 190.762 N/cm³, while the relative densities vary from 87.88 to 99.93%.

Table 3 presents the results of the evaluated soil parameters. In this appraisal, the K_s is determined using the ratio of applied stress and corresponding strain measured using the strain gauge at 0.01 mm strain interval. These parameters serve as the input for regression analysis and subsequent determination of target correlations.

Table 3. Evaluated Soil Parameters

Sr. No	USCS	MC (%)	K_s (N/cm ³)	Q_u (N/cm ²)	RC (%)
1	CL	7	139.519	14.318	87.88
2	CL	8.58	36.775	14.808	89.47
3	CL	8.71	86.481	21.084	90.66
4	CL	8.83	46.672	26.478	91.49
5	CL	9.06	101.869	33.833	98.59
6	CL	9.67	132.324	28.635	93.12
7	CL	9.67	66.221	28.341	93.59
8	CL	10.04	82.189	28.733	94.14
9	CL	10.41	131.127	31.479	93.29
10	CL	11.26	145.733	17.162	91.28
11	CL	11.27	134.196	27.066	96.70
12	CL	11.27	39.275	35.990	99.93
13	CL	11.41	190.762	26.870	94.19
14	CL	11.76	49.414	45.208	99.57
15	CL	12.21	130.407	46.581	98.25
16	CL	12.22	68.549	27.066	94.44
17	CL	12.22	117.341	18.338	88.79
18	CL	12.23	93.030	43.835	98.27
19	CL	13.06	102.007	47.758	97.14
20	CL	13.19	44.732	32.460	94.19
21	CL	13.22	40.133	41.482	98.61
22	CL	13.99	31.439	49.229	99.44
23	CL	14.10	60.805	38.638	99.70
24	CL	14.10	95.381	50.112	99.02
25	CL	14.10	112.905	31.480	95.65
26	CL	14.15	66.0945	45.208	99.46
27	CL	14.15	8.778	36.382	98.56
28	CL	15.47	46.988	30.499	99.48
29	CL	15.61	16.765	29.518	98.73
30	CL	15.61	29.916	28.047	99.58

The study indicates that soil samples at the lower moisture content (6-9%) shown brittle failure before reaching the allowable strain. The soil samples having a moisture content of (10-14%) exhibited shear failure, nearly simultaneous to the allowable strain. The soil samples having higher moisture content undergone a strain of 15% without showing the shear failure. The mode of failures observed for varying MC are identified as brittle for lower moisture content, semi-plastic and plastic for medium and high moisture content. The observed mode of failures from the tested specimens are shown in Figure 6. Cracks developed in the samples with low moisture content propagated vertically, and the samples segregate into many pieces. For the samples with moderate moisture content, cracks propagated diagonally, and the samples show failure just like shear cracks. The samples with high moisture content punch in the middle and show cracks on the sample's outer face.



Figure 6. Modes of Failure with Increasing Moisture

The q_{all} of the samples failed in brittle failure modes ranges from 14.318 N/cm² to 33.833 N/cm² while the q_{all} of samples having MC of 10-14% ranges from 17.162 N/cm² to 49.229 N/cm² and q_{all} of samples having higher moisture content ranges from 28.047 N/cm² to 50.112 N/cm². Stress-strain curves for the modes of failures exhibited at various moisture contents are shown in Figure 7. Although a sample shows excessive strain, the limiting values of strain are taken as 15% as recommended by ASTM, D2166 [41].

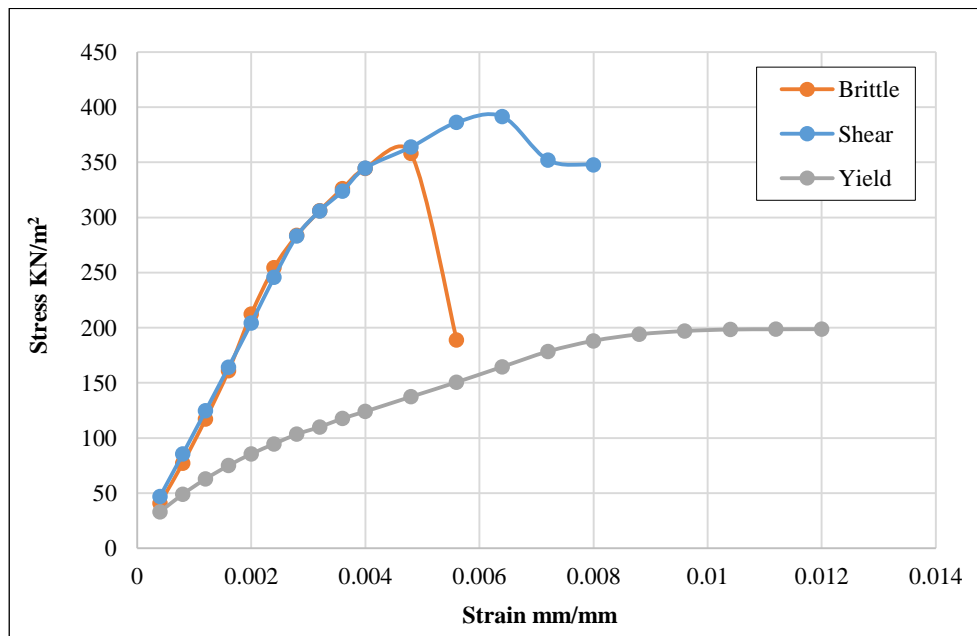


Figure 7. Stress-Strain Curves with Increasing Moisture

At the low moisture content, the samples achieve lower density due to the presence of frictional resistance between soil particles hence leaving the comparatively porous texture of the samples, and results in a brittle failure; with the increase in moisture content, lubrication of the soil surface facilitates rearrangement of soil particles hence bearing higher stress and development of shear-like cracks. The excessive moisture content creates water coating around the soil particles; hence they slide with each other more easily and undergo excessive deformation without showing well-defined failure.

Regression analyses performed using data analysis tools of Microsoft Excel. The input parameters for the determination of q_{all} have acceptable statistical significance. The P-value for the intercept is 0.00047; RC has a P-value of 0.0000097, and the MC is yielding a P-value of 0.94. Multiple R-values for the appraised equation is 0.72, while it is having the coefficient of determination (R^2) of 0.51. The equation developed for Ks; P-value of the intercept remains 0.00248; P-values are 0.0841, 0.016 and 0.00000086 for MC, RC, and UCS respectively. The multiple R-value for the Ks equation is 0.82, while the R^2 is 0.68. The generated correlations are presented as under.

$$q_{all} = 24.18 RC - 6.85 MC - 1912 \tag{3}$$

Where; q_{all} = Allowable Bearing Capacity in (N/cm²); MC = Moisture Content of Soil in (%); RC = Relative Compaction of Soil in (%).

$$K_s = 53.54 + 2.46 UCS - 0.54 MC - 0.5 RC \quad (4)$$

Where; K_s = Modulus of Subgrade Reaction $N/cm^2/cm$; UCS = Unconfined Compressive Strength in N/cm^2 ; MC = Moisture Content in percent; RC = Relative Compaction in percent.

The statistical parameters presented above established the ground for the appraised equations. The moderate correlation is owing to the change in the failure mode with a variation of moisture content. The presented equations can further be strengthened, focusing on the effect of moisture variation on failure modes. The modulus of subgrade reaction has been worked out using the appraisal of Nick Barounis et al. [42].

Although numerous studies correlate different soil properties with compaction characteristics, there is less attention to correlate strength properties derived from relative compaction and moisture content. These correlations require knowledge of other soil parameters that are also difficult to estimate. The available correlations in the accessible literature are presented in Table 4.

Table 4. Comparison of Results

Sr. No.	Proposed Correlation	Reference	Remarks
1	$UCS (N/cm^2) = 24.18 RC - 6.85 MC - 1912$	Current Study	Employ RC and MC
2	$UCS (kN/m^2) = 44.4 Yd - 4.12 MC - 440.25$	[43]	Employ Dry density MC
3	$UCS (kPa) = 35.303 OMC - 522.73$	[44]	Employ Optimum moisture content only
4	$UCS (kPa) = -286.512 MDD + 583.83$	[44]	Employ Maximum Dry Density only
5	$UCS = (kPa) - 40.182 MC + 1290.1$	[45]	Employ MC only
6	$K_s = 53.54 + 2.46 UCS - 0.54 MC - 0.5 RC$	Current Study	Employ UCS., C, and RC
7	$K = E / (B(1 - \nu^2)I)$	[42]	Employ E, Poisson's Ratio and Type of loaded area

5. Conclusion

In this research, the evaluation of refilled soils has been carried to quantify soil bearing capacity improvement associated with the fill's relative compaction. The trend of unconfined compressive strength and modulus of subgrade reaction with the variation in relative compaction and moisture content have been appraised. The Regression analysis of the experimental data performed to establish a correlation of q_{all} with RC and MC . The experimental data has been further utilized to establish a correlation between K_s and UCS , MC , and RC . The proposed relationship will help economical and speedy evaluation of refilled soil to determine the site's suitability for proposed construction and further quantify allowable stress for the situation under consideration. The interpretation and analysis of the experimental data led to identify different modes of failure associated with increasing moisture content. It is also observed that the higher moisture content results in excessive settlements without showing shear failure. For the projects requiring in-situ soil improvement through compaction or the conditions requiring removal and replacement of unsuitable soils, these correlations can help to assess the resulting improvement in the q_{all} . Based on the observations, it is recommended for future studies to evaluate the effect of course content present in the soil, crack patterns, and shrinkage characteristics of the soils on the bearing capacity of the soil.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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