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Research Article

A survey on the relationships between Compression Index, coefficient of consolidation, and atterberg limits

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ABSTRACT

Correlations between compression index and Atterberg limits found in the literature are significant for preliminary estimation. These equations are usually interpreted based on the R-square parameter and classified according to the conditions of the data (disturbed, undisturbed, remolded, etc.). Although correlations reliable enough to eliminate oedometer tests are not yet fully available, these correlations can be helpful in local calculations. In this study, correlations obtained from studies conducted after 2000 on the relationship of compression index and consolidation coefficient with Atterberg limits and water content are mentioned and clearly shown. While the compression index equations are pretty high in the literature, the equations produced with the consolidation coefficient are less in number due to the time-consuming consolidation calculations. Using 105 data from research in the literature, two equations were formed between the compression index, liquid limit, and plasticity index. This study does not propose new equations; only relationships are generated using the Linear Regression method with data obtained from independent studies based on the belief that the compression index has a stronger relationship with the liquid limit and plasticity index.

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1. INTRODUCTION

Maintaining the balance of safety, economy, and aesthetics aimed at engineering studies; requires the design of low-cost, secure structures. Balancing cost and stability is crucial in geotechnical Engineering. Estimating soil parameters by empirical correlation is widely practiced in soil engineering. The main reasons are: that direct measurements are not always applicable and include costly and time-consuming uncertainties. Therefore, empirical correlation can provide a quick and inexpensive way to estimate parameters with a simple test. Most of these correlations are derived from fitting data measurements made under specific site conditions and can cause large deviations when used at other sites. The main research question addressed in this paper is to investigate the applicability of different correlations. The paper is organized as follows. The 'methodology' section presents both the framework of relevant case studies. The following section describes the specifications of the soil samples. A section describes some case studies, linking them with the existing literature. The final section offers a brief discussion and some concluding points. All the research is limited to the year 2000 and later.

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2. REVIEW OF THE EXISTING CORRELATIONS

2.1. Compression Index and Liquid Limit Relations

Compression index (C_c) and coefficient of consolidation (C_v) are two soil characteristics that can determine a soil's compressibility: capacity to reduce volume under pressure (C_v). The coefficient of consolidation is used to forecast how long it will take for a given amount of compression to occur, whereas the compression index is used to estimate settlement. Since Atterberg's limits of the soil's liquid limit (LL) and plastic limit (PL) can be determined quickly, cheaply, and quickly using representative soil samples collected during field exploration [1, 2] efforts have been made to predict the value of compression index of fine-grained soils from these limits ever since. Several scientists have studied the Compression Index and Liquid Limit Relations. Hamza Güllü et al. [3] conducted a study in Baghdad and aimed to establish empirical correlations between soil index properties, water content, liquid limit, initial void ratio (e) and the compression index for 69 fine-grained soil samples. The liquid limit values of the samples ranged from 32% to 62%. The relationship between the Cc and the LL was the most reliable among these correlations. The developed correlation in this study is suitable for the Baghdad region.

$$(C_C=0.00454LL - 0.01246, R^2=0.87) \quad (1)$$

Kok Shien Ng et al. [4] showed a correlation between the C_c with the LL. The study was conducted on five remolded cohesive soil samples with different plasticity properties. The liquid limit values of the samples ranged from 29% to 46%. The correlation of the LL with the C_c presented a very high correlation coefficient.

$$(C_C=0.0062LL + 0.0165, R^2=0.9241) \quad (2)$$

The soil samples used in the study by Kumar K [5] were collected from 6 different regions of India. Fine-grained soils (CH) are classified according to the Indian Standard (IS). The liquid limit values of the samples ranged from 63% to 70%. The R^2 value shows a strong linear relationship between the C_c and the LL.

$$(C_C=0.001(LL) - 0.013, R^2=0.865) \quad (3)$$

In the study of Puri et al. [6], soil samples were collected from North India. Geotechnical data were obtained from 1053 different locations in the state of Haryana. They created different relationships between the C_c and the LL using Linear Regression (LR) Analysis, Artificial Neural Network (ANN), Support Vector Machine (SVM), Random Forest (RF), and M5 Tree (M5P) models. According to R^2 values, the accuracy of the M5P model was found to be the highest. Puri proposed three different empirical correlations according to varying liquid limit ranges. These correlations were suitable for use in Haryana and surrounding areas.

$$(C_C=(0.0092LL) - 0.1091, R^2=0.92)\quad LL\leq 29.25 \quad (4)$$

$$(C_C=(0.0017LL) + 0.1235, R^2=0.92)\quad 29.25< LL <37.35 \quad (5)$$

$$(C_C=(0.0064LL) - 0.0523, R^2=0.92)\quad LL \geq 37.35 \quad (6)$$

Solanki [7] aimed to create empirical correlations between C_c and soil index properties with 135 literature data from 10 regions in Gujarat, India. The mineralogy of soil samples was fine-grained montmorillonite and kaolinite. The liquid limit values of the samples ranged from 30% to 60%. The correlation created in the model produced for shallow foundations provides a strong relationship between the LL and the C_c.

$$(C_C=0.0061LL - 0.0024, R^2=0.8435) \quad (7)$$

Other researchers created empirical correlations through the compression index parameter and soil index properties;

Sridharan and Nagaraj [8] performed conventional consolidation tests on ten soil samples. The initial water contents of these samples were kept almost equal to the liquid limits. While applying traditional consolidation tests, the British Standard is taken as a basis. In the study conducted on remolded clay samples, the liquid limit values of the soil samples ranged from 30% to 60%. The study showed a pretty strong relationship between the C_c and the LL as follows:

$$(C_C=0.008 (LL - 12), R^2=0.8285) \quad (8)$$

Vinod P. and Bindu J. [9] performed studies on remolded marine soil. Eighteen highly plastic soil samples were collected from Kerala in India with gray and black marine clay characteristics. The liquid limit values of the soil samples ranged from 70.8% to 276.3%. The correlation between the C_c and the LL as a result of this study was developed, which had a perfect correlation coefficient.

$$(C_C=0.0055 (LL - 1.8364), R^2=0.9407) \quad (9)$$

Slamet W. and Abdelazim I. [10] studied 20 samples collected from 10 boreholes in Pontianak, Indonesia. Independent variables associated with the compression index were; void ratio, water content, and liquid limit. The liquid limit values of the soil samples ranged from 17.1% to 62.46%. In the correlation between the C_c and the LL, the R^2 value showed that the relationship between the two parameters is weak.

$$(C_C=0.01706 LL - 0.02209, R^2=0.349) \quad (10)$$

Zaman et al. [11] used 14 undisturbed clay samples their study collected from Bangladesh. The liquid limit values of the soil samples ranged from 33.73% to 67.097%. The correlation between the C_c and the liquid limit was quite strong. This equation was suitable for use in Bangladesh soils.

$$(C_C=0.01\ (LL - 13.61),\ R^2=0.9805) \tag{11}$$

Binod Tiwari and Beena Ajmera [12] obtained 82 different natural samples by mixing montmorillonite, illite, kaolinite, and quartz in the laboratory. The soil samples in the study were collected from natural disaster areas in Japan. As a consequence of this study, the correlations between C_c and LL were determined as two types. The first of these (12) was for soils having activity less than 1.

$$(C_C=0.0075(LL),\ R^2=0.920) \tag{12}$$

The equation proposed for soils with activity greater than 1 is very efficient with R^2 value.

$$(C_C=0.012(LL),\ R^2=0.943) \tag{13}$$

It was observed that most montmorillonite soil samples have an activity greater than 1. The researchers stated that the empirical equations created with the LL showed the highest performance among the correlations they created between the C_c and other soil index properties.

In the study executed by Amit N. and S.S. DeDalal [13], they used 50 samples mixed with river sand and clay in different proportions. They mainly used bentonite and kaolinite, collected from West Bengal, India. Fourteen of the samples were classified as CH (High-plastic clay), 14 of the samples as CI (Intermediate-plastic clay), 20 samples as CL (Low-plastic clay), Low plastic silty- clayey soil (CL-ML), and a plastic limit of 1 sample could not be determined. In the study, C_c and LL together showed high compliance.

$$(C_C=0.0124LL - 0.1761,\ R^2=0.993) \tag{14}$$

Ayşen Lav and Atilla Ansal [14] suggested correlations between the compression and soil index parameters. For this study, they used 300 soil specimens collected from laboratory data in Türkiye. The liquid limit values of the soil samples ranged from 23% to 166%. They presented an insufficient relationship between C_c and LL for all soils (Eq. 15). They suggested another correlation for Normally-Consolidated clays (NC) with sufficient R^2 value (Eq. 16).

$$(C_C=0.006\ (LL + 1),\ R^2=0.509) \tag{15}$$

$$(C_C=0.007LL - 0.029),\ R^2=0.661) \tag{16}$$

Gil Lim Yoon et al. [15] used 1200 marine clay samples collected from 3 different regions of Korea to establish correlations between C_c and soil index properties. Undisturbed soil samples were classified as CL, CH, Low-Plastic Silt (ML), and High-Plastic Silt (MH). Three hundred fifty-six soil samples were used for the west coast, and their liquid limits ranged from 24.5% to 77.9%. 603 samples were used for the east coast, and liquid limits ranged from 23% to 107%. 278 soil samples were used for the south coast, with liquid limit values ranging from 28.4% to 120.2%. Relatively strong correlations were observed between the C_c and the LL.

$$(C_C=0.012(LL + 16.4),\ R^2=0.64)\ \text{South coast} \tag{17}$$

$$(C_C=0.011(LL - 6.36),\ R^2=0.64)\ \text{East coast} \tag{18}$$

$$(C_C=0.01(LL - 10.9),\ R^2=0.67)\ \text{West coast} \tag{19}$$

Akayuli and Ofosu [16] aimed to produce correlations between C_c and Atterberg limit properties by performing tests on 90 soil samples collected from Kumasi in Ghana. 60 of these samples were used directly in the model, and the other 30 were used to confirm the model in the estimation of the C_c. The samples used in the study were taken from the laboratory and collected under the same conditions. Samples were classified as weathered Brimian phyllites; their liquid limits ranged from 14.6% to 67.6%. As a result of the research, a reasonable correlation has been developed between the C_c and the LL for use in this region.

$$(C_C=0.004LL - 0.03,\ R^2=0.784) \tag{20}$$

Kumar, Jain, et al. [17] created empirical equations in their study using soil samples collected from 16 different regions of Bhopal, India. Soil samples were classified as nine black-cotton soils, four red soils, three yellow soils, two bentonite soils, and five black-cotton soils with different proportions of bentonite. Their liquid limit values ranged from 41.28% to 140.56%. They used ten soil samples under the same conditions to verify their proposed equation. As a result of the study, C_c has a strong relationship with LL.

$$(C_C=0.0067\ (LL) - 0.0364,\ R^2=0.94) \tag{21}$$

Salih [18] worked on soil samples from various Iraq regions. While obtaining this correlation, 76 undisturbed soil samples were used, and their liquid limit values ranged from 30% to 70%. As a result of this study, it was observed that there was a weak correlation between C_c and LL.

$$(C_C=-0.0037LL + 0.352,\ R^2=0.46) \tag{22}$$

Al-Khafaji et al. [19] aimed to generate new empirical equations using 1906 samples from previous studies. They used Robust Bi-Square software in MATLAB to avoid data outliers and obtain more realistic results. First, they produced a correlation (23) for LL >16 using conventional regression analysis. The authors stated that a low Root Mean Square Error (RMSE) value means that the model is 95% reliable. Then an equation (24) was created using Robust Bi-Square. This equation (24) provided higher accuracy with a lower RMSE and was deemed suitable for liquid limit values LL >17. Since most of the mineral soils are evaluated in the 16< LL <100, a reanalysis was performed on the data in this range using Robust Bi-Square. The equation (25) was created as a result of this analysis. The equations (24) and (25) obtained using Robust Bi-Square were almost similar and suitable for use in samples within the specified liquid limit ranges.

$$(C_C=-0.1096 + 0.01049LL, R^2=0.7688) \quad (23)$$

$$(C_C=-0.012 (LL - 17), R^2=0.8617) \quad (24)$$

$$(C_C=0.0116 (LL - 16.6), R^2=0.7066) \quad (25)$$

Dway and Thant [20] studied six disturbed samples collected at 3 and 6 feet from 3 locations in Mandalay. Four of the soil samples were classified as CH (High- Plastic Clay) and 2 as CL (Low- Plastic Clay), and their liquid limit values ranged from 41% to 70.1%. Correlations between C_c and soil index properties were established using linear regression. The proposed equation between the LL and the C_c has been found to have a low correlation coefficient and cannot be used to predict the compression index.

$$(C_C=0.0027LL + 0.1994, R^2=0.250) \quad (26)$$

In the study presented by Laskar and Pal [21], they studied three different soil samples collected from different regions of India. The study observed that the correlation between the C_c and the LL was quite reliable.

$$(C_C=0.0046(LL -1.39), R^2=0.994) \quad (27)$$

Abbasi et al. [22] estimated the C_c using 26 soil samples from 5 provinces of Iran. The soil samples used in this study were fine-grained and disturbed. The researchers took care that the liquid limit values of the soil samples were below 75. As a result of the study, the correlation between the C_c and the LL was found to be insufficient.

$$(C_C=0.007LL - 0.043, R^2=0.351) \quad (28)$$

Bartlett and Lee [23] found a weak relationship between the LL and the C_c in their study in Salt Lake Valley.

$$(C_C=0.01LL - 0.026, R^2= 0.3129) \quad (29)$$

McCabe et al. [24] aimed to establish empirical relationships between C_c and soil index properties in fine-grained soils of Ireland. In this study, 61 soil samples were collected from different parts of Ireland, and the liquid limit values ranged between 32% and 199%. The empirical equation formed between the C_c and the LL has been found suitable for local prediction. The R^2 value of the equation was found to be entirely satisfactory.

$$(C_C=0.0118LL - 0.2443, R^2=0.809) \quad (30)$$

Nesamatha and Arumairaj [25] wanted to estimate the C_c by conducting tests on five soil samples collected from different parts of Coimbatore, India. Soil samples were remolded in black cotton soil. The liquid limit values of soils ranged between 66.2% to 77.8%. The R^2 value showed that the LL is very influential in the estimation of the C_c.

$$(C_C=0.002LL - 0.127, R^2=0.9694) \quad (31)$$

Rashed et al. [26] proposed a correlation using 54 undisturbed soil samples from Sulaymaniyah, Iraq. The liquid limit values of the soil samples varied between 35.5% and 65.2%. The equation was found sufficient to be used in preliminary estimating the compression index.

$$(C_C=0.006LL - 0.1, R^2=0.74) \quad (32)$$

In the study of Al-Ameri and Al-Kahdaar [27] soil samples were collected from Ammarah, Iraq. Soil samples obtained from 40 different locations, selected from geotechnical reports, and brought together, were evaluated as low to high-plasticity clays. The LL values of soil samples ranged from 22% to 62%. Linear regression analysis was used to create the empirical correlation. It was observed that there is a strong relationship between the C_c and the LL.

$$(C_C=0.00556LL, R^2=0.868) \quad (33)$$

Shaikh et al. [28] studied soil samples collected from Khulna, Bangladesh. A lot of soil structure is being made on the organic soils of Khulna city with poor bearing capacity; this study was carried out to quickly obtain a preliminary estimate of the C_c in the studies conducted in this region. The LL values of soil samples ranged between 29% to 68%. According to this study, it is seen that there is a powerful relationship between C_c and LL.

$$(C_C=0.011LL - 0.102, R^2= 0.818) \quad (34)$$

Kootahi and Moradi [29] studied approximately 500 marine clay samples from 1000 different locations worldwide from 170 different data sources. These soil samples were obtained from the studies of 40 different researchers.

The intact ones were chosen among these samples for the estimation of the C_c on marine clays. It is stated that most of the marine clays were collected from Southeast and South Asia, Northern Europe, and North and South America. Marine clays had different physical and engineering properties. Researchers classified 70% of marine clays as CH-CL and 30% as MH-ML. The correlation created from this detailed study showed that the C_c has a strong relationship with the LL parameter.

$$(C_C=-0.096 + 0.012LL, R^2=0.87) \quad (35)$$

Ara S et al. [30] used eight undisturbed soil samples collected from Chattagram city. As a result of this study, a strong relationship was established between Cc-LL.

$$(C_C=0.0046LL + 0.2324, R^2=0.9137) \quad (36)$$

2.2. Compression Index and Plasticity Index Relations

Bello et al. [31] studied eight migmatite-gneiss-derived laterite samples collected from Southwest Nigeria. Soils were classified as 37% low-plastic clay (CL), 37% medium-plastic clay (CI), 13% high-plastic clay (CH), and 13% medium-plasticity clay (MI). The plasticity index (PI) values ranged between 8% to 33.65%. Bello established correlations between the C_c and SI (Shrinkage Index), which is the range between liquid limit and shrinkage limit, LS (Linear Shrinkage), which shows a decrease in one dimension of soil expressed as a percentage of its original dimension, when the water content is reduced from its given value up to shrinkage limit, and PI. The most effective of these correlations was found to be the relation between the C_c and the PI.

$$(C_C=0.0028PI - 0.0052, R^2=0.90) \quad (37)$$

Kok Shien Ng et al. [4] also found a correlation between the C_c and the PI. The PI values of soil samples ranged from 8% to 18%. Although this correlation is not very strong, it is usable without other index properties.

$$(C_C=0.0032PI + 0.1817, R^2=0.7186) \quad (38)$$

Solanki [7] also presented a correlation between C_c and PI. PI values of soil samples ranged from 15% to 30%. The R^2 value was satisfactory, although not as good as the liquid limit correlation.

$$(C_C=0.0082PI + 0.0915, R^2=0.7862) \quad (39)$$

The equation proposed by Vinod P. and Bindu J. [9] was created for use in remolded marine soils. PI values ranged from 34.8% to 235.5%. The coefficient of this correlation was found to be relatively high.

$$(C_C=0.0086 (PI + 24.2674), R^2=0.970) \quad (40)$$

The correlation suggested by Zaman et al. [11] also showed a strong relationship between the C_c and the PI. In this study, PI values of soil samples ranged between 12.083% to 44.287%.

$$(C_C=0.0091PI + 0.128, R^2=0.8864) \quad (41)$$

Like other researchers, Sridharan and Nagaraj [8] suggested a strong correlation between C_c and PI. The plasticity indexes of the soil samples ranged from 9.5% to 37.9%.

$$(C_C=0.014 (PI + 3.6), R^2=0.91) \quad (42)$$

In Akayuli and Ofosu [16] study, when they examined the relationship between the C_c and PI, the R^2 value showed a good relationship.

$$(C_C=0.007PI + 0.01, R^2=0.580) \quad (43)$$

Gil Lim Yoon et al. [15] studied marine clay in Korea. Soil samples are divided into three subgroups according to their plasticity characteristics as the east, west, and south coasts. The relationship between C_c and PI was created only for the east coast compared to other soil index properties. This correlation demonstrated a good relationship between the C_c and PI.

$$(C_C=0.014PI + 0.165, R^2=0.61) \quad (44)$$

Salih [18] worked with soil samples he collected from Sulaymaniyah city in Iraq. The correlation he created as a result of this study showed that the PI is unsuitable for finding the C_c.

$$(C_C=-0.0049PI + 0.2882, R^2=0.44) \quad (45)$$

The correlation established by Dway and Thant [20] presented an inadequate relationship. In this study, the PI values of soil samples ranged between 25% and 48.8%.

$$(C_C=0.0038 PI + 0.22, R^2=0.303) \quad (46)$$

In the article they published, Laskar and Pal [21] worked on only three soil samples. Plasticity index values ranged from 5% to 35%, and the correlation presented a relatively high R^2 value.

$$(C_C=0.0058 (PI+13.776), R^2= 0.991) \quad (47)$$

Barlett and Lee [32] presented a relatively low correlation for C_c estimation.

$$(C_C=0.0099PI + 0.2039, R^2=0.1789) \quad (48)$$

Nesamatha and Arumairaj [25] used 5 different remolded stiff clays collected from India in this study. They established a correlation with Regression Analysis in Eq. (49). The R^2 value was relatively high.

$$(C_C=0.003PI - 0.081, R^2=0.91) \quad (49)$$

The study of Rashed et al. [26] was conducted using 46 undisturbed fine-grained soil samples collected from Iraq. The plasticity indexes of these soil samples ranged from 15.26% to 28.2%. According to the empirical equation, a strong correlation was found between the C_c and the PI.

$$(C_C=0.007PI + 0.04, R^2=0.72) \quad (50)$$

Shaikh et al. [28] derived a robust correlation between the C_c and the PI using organic clays with poor bearing strength from Khulna city, Bangladesh.

$$(C_C=0.017PI + 0.180, R^2=0.904) \quad (51)$$

Jain et al. [33] conducted research using 44 soil samples from geotechnical studies in various regions of India. The samples were laboratory data obtained under the same conditions. The empirical equation they produced was found to be reasonably sufficient for the estimation of the C_c. It was stated that the equation in this study is valid for soil samples with PI values between 5 and 35 percent.

$$(C_C=0.0082PI + 0.0475, R^2=0.8984) \quad (52)$$

Kootahi and Moradi's [29] study used data from approximately 500 marine clay samples from different researchers' studies. The soil samples used in this study had different plasticity and consolidation properties. As a result, the relationship between the C_c and the PI was found to be entirely satisfactory.

$$(C_C=0.013 + 0.020PI, R^2=0.85) \quad (53)$$

2.3. Compression Index and Plastic Limit Relations

Few studies in the literature examined the relationship between C_c and PL. One of these studies is by Kok Shien Ng et al. [4]. As a result of the study, a sufficiently good relationship was observed between these two parameters.

$$(C_C=0.0133PL - 0.0833, R^2=0.6809) \quad (54)$$

Akayuli and Ofosu [16] also correlated the C_c and PL. They created an invalid relationship between these two parameters in their study on Brimian phyllites in the Kumasi area.

$$(C_C=0.003PL + 0.055, R^2=0.43) \quad (55)$$

Another study that presented a strong correlation between the PL and the C_c was by Rashed et al. [26]. In this study, 45 undisturbed soil samples were used, and these samples were selected from among 60 samples collected from various parts of the Iraqi city of Sulaymaniyah. The PL values of these samples varied between 20 and 37 percent. The empirical correlation they created presented an excellent relationship.

$$(C_C=0.007PL - 0.005, R^2=0.75) \quad (56)$$

Ara S et al. [30] proposed a weak correlation between C_c and PL.

$$(C_C=0.0024PL + 0.3705, R^2=0.3113) \quad (57)$$

2.4. Compression Index and Water Content Relations

Vinod P. and Bindu J. [9] developed a reasonably strong correlation between C_c and natural water content (w_n). The wn values of these samples varied between 64.7 and 184.3 percent. This correlation is suitable for use for marine clays in India.

$$(C_C=0.0072 (w_n - 12.625), R^2=0.878) \quad (58)$$

Solanki [7] also created a correlation between the C_c and water content on soil samples collected from India. The soil samples' water content values ranged from 15% to 30%. The R^2 produced an excellent relationship.

$$(C_C=0.0091w_n + 0.0522, R^2=0.77) \quad (59)$$

Slamet W. and Abdelazim I. [10] produced an imperfect correlation between C_c and natural water content.

$$(C_C= 0.01w_n + 0.12, R^2=0.24) \quad (60)$$

The correlation suggested by Zaman et al. [11] was strong and suitable for use in Bangladesh soils and similar types of soils.

$$(C_C=0.0158w_n - 0.179, R^2=0.8997) \quad (61)$$

Alptekin and Taga [33] performed Atterberg tests on 58 soil samples collected from Türkiye's Mersin city; samples were selected as 18 marine and 40 terrestrials. 4 were not plastic, so Atterberg tests were not performed on these four samples. The soil samples used in this study were undisturbed. For this reason, it is thought that more realistic results are obtained.

$$(C_C=0.0064w_n - 0.0607, R^2=0.598) \quad (62)$$

Soil samples used in the study of Lav and Ansal [14] were collected from Türkiye's different regions. Additionally, the authors divided the 300 soil samples into subgroups according to their consolidation properties. Relatively strong correlations were found between the water content and the C_c. The correlation produced for all soil is as seen in Eq. (63). Eq. (64) was produced for normally consolidated clays.

$$(C_C=0.012w_n - 0.1, R^2=0.758) \quad (63)$$

$$(C_C=0.012w_n - 0.098, R^2=0.877) \quad (64)$$

Soil samples used in the research by Yoon et al. [15] were collected from various regions of Korea. The 1200 data used in this study were characterized as undisturbed marine clay. Correlations were created for soils specific to 3 different regions of Korea. While estimating the C_c, it was understood that the water content would be sufficient for each coast.

$$(C_C=.013(wn - 3.85), R^2=0.73) \text{ South coast} \quad (65)$$

$$(C_C=0.01(w_n + 2.83), R^2=0.54) \text{ East coast} \quad (66)$$

$$(C_C=0.011(w_n - 11.22), R^2=0.67) \text{ West coast} \quad (67)$$

Güllü et al. [3] conducted a study suggesting a correlation between C_c and natural water content. The correlation established on 69 fine-grained soil samples obtained from Baghdad city is suitable for use in the Baghdad region.

$$(C_C=0.00553w_n + 0.05321, R^2=0.53) \quad (68)$$

In the study of Akayuli and Ofosu [16], the correlation they formed between the C_c and the moisture content was considered to be weak for the Ghana region.

$$(C_C=0.002w_n + 0.14, R^2=0.382) \quad (69)$$

In the research of Sari and Firmansyah [34] 425 of 466 soil samples obtained from 25 different regions in Indonesia were used. This research was carried out to compare the correlations in the literature and check their suitability for use. Samples were divided into subgroups. Correlations were not suitable for use.

$$(C_C=0.0143w_n - 0.0165, R^2=0.5102)$$
$$LL=0 - 100\%; PI=0 - 70\% \quad (70)$$

The empirical equation proposed by Dway and Thant [20] between w_n and C_c was found to be moderately usable.

$$(C_C=0.01w_n + 0.027, R^2=0.491) \quad (71)$$

In their study, Laskar and Pal [21] used 3 different soil samples, and the water contents varied between 15 and 32 percent.

$$(C_C=0.0134 (w_n - 7.034), R^2=0.985) \quad (72)$$

Abbasi et al. [22] correlated the water content and the compression index using 26 fine-grained soil samples collected from different regions of Iran. Most of the soil samples were classified as low-plasticity clay. The correlation coefficient given by this correlation showed a strong relationship between these two parameters.

$$(C_C=0.008w_n - 0.044, R^2=0.848) \quad (73)$$

In the study presented by Barlet and Lee [23], it was observed that there is a sufficiently strong correlation between the natural water content and the C_c.

$$(C_C=0.0163w_n - 0.247, R^2=0.6572) \quad (74)$$

McCabe et al. [24] examined 61 soil samples in their study on Irish soil. The water contents of these samples ranged from 34.7% to 244.1%. A robust correlation was observed between the C_c and the natural water content. Although this equation is unsuitable for use instead of oedometer tests in Irish soil, it was found to be reasonably sufficient in terms of preliminary prediction.

$$(C_C=0.014w_n - 0.3175, R^2=0.858) \quad (75)$$

Al-Ameri and Al-Kahdaar [27] produced an empirical equation using 40 different soil sample data from geotechnical reports in Ammarah, Iraq. The R^2 value of this equation showed that a powerful equation was presented.

$$(C_C=0.0092w_n, R^2=0.946) \quad (76)$$

The equation by Kootahi and Moradi [29] is proposed for marine clays. These marine clays were collected from studies in the literature from different parts of the world. The R^2 value of the equation showed that the water content parameter could be used to estimate the C_c.

$$(C_C=-0.093 + 0.012w_n, R^2=0.91) \quad (77)$$

2.5. Coefficient of Consolidation Relations

Kassou et al. [35] studied settling and consolidation rates in the High-Speed Rail Project in Morocco. They showed that the elastic method using the pressure-gauge modulus gives more accurate results than the iodometric method. This correlation they produced agrees with the US Navy correlation and the C_v estimate.

$$(C_V=26.917LL - 2.57) \quad (78)$$

Asma Y. and Abbas F. [36] tried to estimate and define the relationship between the C_V and LL in their studies in Central and Southern Iraq. The soil samples consisted of 280 undisturbed silty clay. The Casagrande method was used in liquid limit calculations, and Taylor's Square Root of Time Method was used in calculating the consolidation coefficient. Comparing data from Iraqi soil with data from other studies (US Navy study), it was seen that the curves overlap when LL equals 60, and there are deviations when it is less than or greater than 60. The presented curve was compared with the curve formed by the US Navy, and it was observed that the curves agree at one point (LL=60). As a result of the study, a good relationship was established between CV and LL.

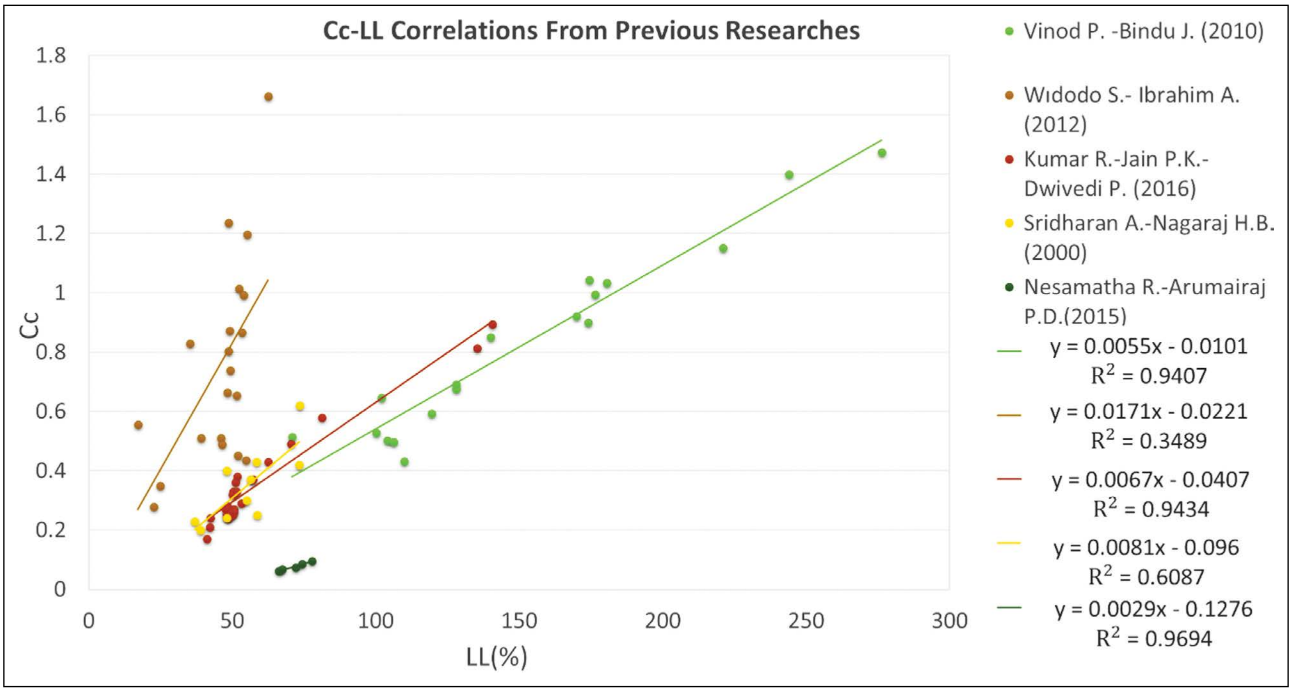

Figure 1. Relationships between C_c and LL.

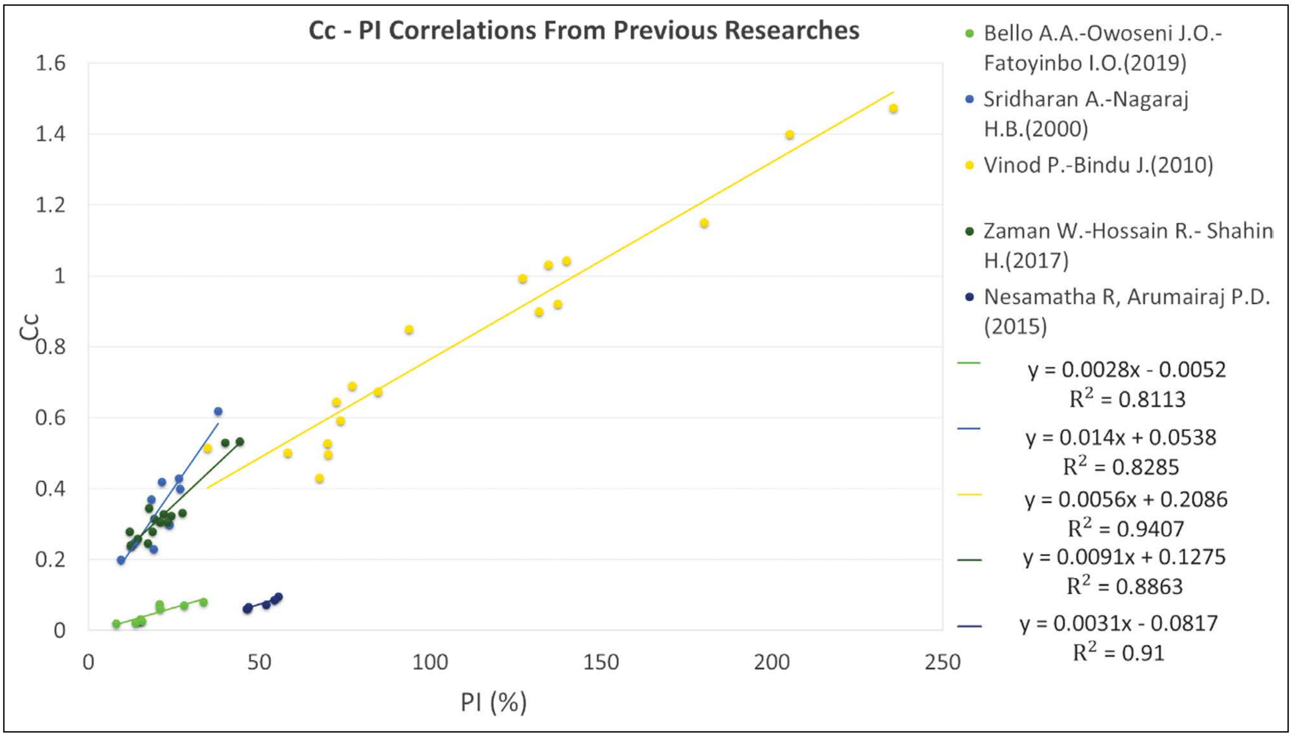

Figure 2. Relationships between C_c and PI.

$$(C_V=4258LL^{-1.758},\ R^2=0.721) \tag{79}$$

Devi et al. [37] produced correlations between the consolidation coefficient and the Atterberg limit properties. Soil samples were collected from different regions in the Manipur Valley (India). The five undisturbed samples included clay, silt, sand, and organic content. C_V values were calculated by the Casagrande method. Among the liquid limit, plasticity index, and shrinkage indices, it was seen that the CV was better associated with the LL.

$$(C_V=-4x10^{-9}\ LL + 4x10^{-7},\ R^2=0.8298) \quad (80)$$

$$(C_V=-1x10^{-7}\ \ln(PI) + 6x10^{-7},\ R^2=0.5954) \quad (81)$$

$$(C_V=1x10^{-6}\ e^{-0.064IS},\ R^2=0.6132) \quad (82)$$

Solanki's [7] study aimed to predict the consolidation parameters in alluvial deposits as much as possible. This study was conducted with data collected from 10 different regions of Surat (India). Soil samples contained montmorillonite and kaolinite clay. It was studied with 135 test data obtained from the literature. Correlations of C_V with LL and PI were found to be entirely satisfactory.

$$(C_V=7.7525PI^{-3.1025},\ R^2=0.9156) \quad (83)$$

$$(C_V= 10^8\ LL^{-6.7591},\ R^2=0.7867) \quad (84)$$

Kok Shien Ng et al. [4] examined the relationships between C_V and Atterberg limits conducted on five cohesive soil samples in Malaysia. Samples were designated as CI, CL, MI, and CI. C_V values were determined by the Taylor method. It was concluded that C_V was best associated with PI. The relationship with LL also gave good results.

$$(C_V=0.6155 -0.0183PI,\ R^2=0.9599) \quad (85)$$

$$(C_V=0.7519 - 0.0102LL,\ R^2=0.8608) \quad (86)$$

$$(C_V=0.859 - 0.0202PL,\ R^2=0.6505) \quad (87)$$

In this experimental study, Sridharan and Nagaraj [38] investigated the relationships between C_V and LL, PI, and Shrinkage Index (SI) on ten disturbed soil samples. Soil samples contained varying proportions of silt, sand, and mainly kaolinite clay. As a result of the study, it was found that C_V had a good relationship with the plasticity index, and the best relationship was with the shrinkage index.

$$(C_V=4{,}3x10^7\ (PI)^{-4.7},\ R^2=0.6087) \quad (88)$$

$$(C_V=3x10^{-2}\ (SI)^{-3{,}54},\ R^2=0.8836) \quad (89)$$

Bello et al. [31] studied eight disturbed samples in southwestern Nigeria. The liquid limit values of the samples were almost the same. As a result of the studies, it was observed that the correlation between C_V and PI was more substantial than other parameters.

$$(C_V=1x10^{-9}\ PI^{-0{,}35},\ R^2=0.62) \quad (90)$$

Jadhav's experimental work [39] was carried out on 20 different soil samples from different parts of Begaldot district, Karnataka state, India. At the end of the study, it was found that the relationship between the coefficient of consolidation and shrinkage index (SI) was.

$$(C_V=128.7/\ (SI)\ 3.54 + 0.0002,\ R^2=0.715) \quad (91)$$

Shaikh e al. [28] correlated the consolidation coefficient with LL and PI in 2 relationships. The R^2 values of these relations were found to be entirely satisfactory.

$$(C_V=0.241e^{-0.08LL},\ R^2=0.818) \quad (92)$$

$$(C_V=0.022e^{-0.12PI},\ R^2=0.790) \quad (93)$$

In the study of Vinod P. and Bindu J. [9], the slope value of the correlation they created between the compression index and the plasticity index was given as 0.0086 in Eq. (40). However, the slope value was found to be 0.0056 in the equation reconstructed with the help of linear regression as seen in Figure 1. In addition, the R-square value was calculated and found to be 0.9407 in Eq. (94).

$$(C_C=0.0056PI + 0.2086,\ R^2=0.9407) \quad (94)$$

Figure 2 depicts the relationship between CC and PI. Data obtained from several research have been compared with each other. As it can be seen, the correlation factors show a good consistency between the mentioned parameters.

3. MATERIALS AND METHODS

In this part, the studied results are gathered in Table 1. The selected soil types include Low- Plastic soils (L) and High- Plastic Soils (H). Correlations were created with the linear regression method using the data obtained from the literature. The linear correlations between C_c, LL, and PI are shown in Figure 3 and Figure 4.

4. RESULTS

This research studied the published correlations between the plasticity index, compression index, liquid limit, plastic limit, water content, and coefficient of consolidation. The relations were determined based on the coefficient of correlation values. Equations between C_c, LL, and PI variables were created with the help of Linear Regression using independent data from 5 different studies. These soil samples were obtained under different conditions and are from different regions. In C_c and LL correlation, 87 samples were used, and the liquid limit values ranged from 20.5% to 479.9%. The R-Square value of this correlation was found to be 0.925, which indicates a strong relationship between the two parameters. For the correlation between the compression index and the plasticity index, 61 soil samples were used, and these samples were obtained under different conditions. The plasticity index values of these samples varied between

Table 1. List of the used data in the compression index estimation

No.	LL	PI	CC	Location	Author	No.	LL	PI	CC	Location	Author
1	88	40.23	0.747895	Manipur, India	Devi et al.	54	36	–	0.12	New Delhi, India	Kumar Jain et al.
2	58.65	24.09	0.244034	Manipur, India	Devi et al.	55	39.4	–	0.106	New Delhi, India	Kumar Jain et al.
3	76.2	50.65	0.257034	Manipur, India	Devi et al.	56	46	–	0.226	New Delhi, India	Kumar Jain et al.
4	62.1	32.96	0.258915	Manipur, India	Devi et al.	57	37	–	0.2	New Delhi, India	Kumar Jain et al.
5	52.4	22.53	0.14537	Manipur, India	Devi et al.	58	45.5	–	0.32	New Delhi, India	Kumar Jain et al.
6	66	32.3	0.32	Ariake, Japan	Park, Koumoto [40]	59	50	–	0.38	New Delhi, India	Kumar Jain et al.
7	66	32.3	0.35	Ariake, Japan	Park, Koumoto	60	46.5	–	0.35	New Delhi, India	Kumar Jain et al.
8	66	32.3	0.37	Ariake, Japan	Park, Koumoto	61	20.5	–	0.102	New Delhi, India	Ibrahim et al. [40]
9	50.4	32.8	0.23	Ariake, Japan	Park, Koumoto	62	28.7	–	0.092	New Delhi, India	Kumar Jain et al.
10	50.4	32.8	0.27	Ariake, Japan	Park, Koumoto	63	43.4	–	0.17	New Delhi, India	Kumar Jain et al.
11	50.4	32.8	0.31	Ariake, Japan	Park, Koumoto	64	30.7	–	0.16	New Delhi, India	Kumar Jain et al.
12	72.1	34.8	0.28	Ariake, Japan	Park, Koumoto	65	44	–	0.15	New Delhi, India	Kumar Jain et al.
13	72.1	34.8	0.38	Ariake, Japan	Park, Koumoto	66	31.1	–	0.15	New Delhi, India	Kumar Jain et al.
14	72.1	34.8	0.42	Ariake, Japan	Park, Koumoto	67	31.9	–	0.166	New Delhi, India	Kumar Jain et al.
15	81.7	39.7	0.33	Ariake, Japan	Park, Koumoto	68	29.5	–	0.176	New Delhi, India	Kumar Jain et al.
16	81.7	39.7	0.4	Ariake, Japan	Park, Koumoto	69	29.1	–	0.114	New Delhi, India	Kumar Jain et al.
17	81.7	39.7	0.45	Ariake, Japan	Park, Koumoto	70	42.6	–	0.23	New Delhi, India	Kumar Jain et al.
18	86.6	42.3	0.34	Ariake, Japan	Park, Koumoto	71	44.1	–	0.24	New Delhi, India	Kumar Jain et al.
19	86.6	42.3	0.4	Ariake, Japan	Park, Koumoto	72	45.8	–	0.179	New Delhi, India	Kumar Jain et al.
20	86.6	42.3	0.53	Ariake, Japan	Park, Koumoto	73	35.6	–	0.129	New Delhi, India	Kumar Jain et al.
21	78.6	47.5	0.56	Ariake, Japan	Park, Koumoto	74	27.1	–	0.16	New Delhi, India	Kumar Jain et al.
22	138.6	70	0.6	Ariake, Japan	Park, Koumoto	75	28.6	–	0.093	New Delhi, India	Kumar Jain et al.
23	138.6	70	0.72	Ariake, Japan	Park, Koumoto	76	33.9	–	0.126	New Delhi, India	Kumar Jain et al.
24	138.6	70	1	Ariake, Japan	Park, Koumoto	77	34.2	–	0.152	New Delhi, India	Kumar Jain et al.
25	166.2	113.9	0.91	Ariake, Japan	Park, Koumoto	78	34.8	–	0.166	New Delhi, India	Kumar Jain et al.
26	166.2	113.9	1.16	Ariake, Japan	Park, Koumoto	79	24.7	–	0.168	New Delhi, India	Kumar Jain et al.
27	166.2	113.9	1.34	Ariake, Japan	Park, Koumoto	80	34	–	0.124	New Delhi, India	Kumar Jain et al.
28	361.9	317.5	1.62	Ariake, Japan	Park, Koumoto	81	25.3	–	0.182	New Delhi, India	Kumar Jain et al.
29	361.9	317.5	2.27	Ariake, Japan	Park, Koumoto	82	30.6	–	0.135	New Delhi, India	Kumar Jain et al.
30	361.9	317.5	3.02	Ariake, Japan	Park, Koumoto	83	25.5	–	0.13	New Delhi, India	Kumar Jain et al.
31	479.9	443.7	2.87	Ariake, Japan	Park, Koumoto	84	27.8	–	0.13	New Delhi, India	Kumar Jain et al.
32	479.9	443.7	3.65	Ariake, Japan	Park, Koumoto	85	27	–	0.2	New Delhi, India	Kumar Jain et al.
33	479.9	443.7	4.76	Ariake, Japan	Park, Koumoto	86	30.5	–	0.173	New Delhi, India	Kumar Jain et al.

Table 1 (cont.). List of the used data in the compression index estimation

No.	LL	PI	CC	Location	Author	No.	LL	PI	CC	Location	Author
34	50	30	0.184	Southern England	Jones, Hobbs [41]	87	31.3	–	0.114	New Delhi, India	Kumar Jain et al.
35	57	33	0.197	Southern England	Jones, Hobbs	88	–	28.33	0.258	Perlis, Malaysia	Ibrahim et al.[42]
36	46	25	0.212	Southern England	Jones, Hobbs	89	–	29.10	0.265	Perlis, Malaysia	Ibrahim et al.
37	50	30	0.16	Southern England	Jones, Hobbs	90	–	30.14	0.456	Perlis, Malaysia	Ibrahim et al.
38	64	36	0.286	Southern England	Jones, Hobbs	91	–	29.38	0.723	Perlis, Malaysia	Ibrahim et al.
39	49	23	0.18	Southern England	Jones, Hobbs	92	–	30.10	0.764	Perlis, Malaysia	Ibrahim et al.
40	45	24	0.191	Southern England	Jones, Hobbs	93	–	32.75	0.918	Perlis, Malaysia	Ibrahim et al.
41	47	29	0.18	Southern England	Jones, Hobbs	94	–	30.76	0.506	Perlis, Malaysia	Ibrahim et al.
42	48	23	0.171	Southern England	Jones, Hobbs	95	–	30.24	0.270	Perlis, Malaysia	Ibrahim et al.
43	54	34	0.228	Southern England	Jones, Hobbs	96	–	31.70	0.968	Perlis, Malaysia	Ibrahim et al.
44	46.6	–	0.265	New Delhi, India	Kumar Jain et al.	97	–	30.49	0.940	Perlis, Malaysia	Ibrahim et al.
45	45	–	0.169	New Delhi, India	Kumar Jain et al.	98	–	29.07	0.607	Perlis, Malaysia	Ibrahim et al.
46	42.5	–	0.213	New Delhi, India	Kumar Jain et al.	99	–	28.09	0.387	Perlis, Malaysia	Ibrahim et al.
47	43.1	–	0.219	New Delhi, India	Kumar Jain et al.	100	–	28.47	0.101	Perlis, Malaysia	Ibrahim et al.
48	44.7	–	0.133	New Delhi, India	Kumar Jain et al.	101	–	28.80	0.341	Perlis, Malaysia	Ibrahim et al.
49	30	–	0.133	New Delhi, India	Kumar Jain et al.	102	–	30.04	0.723	Perlis, Malaysia	Ibrahim et al.
50	59.7	–	0.259	New Delhi, India	Kumar Jain et al.	103	–	27.49	0.186	Perlis, Malaysia	Ibrahim et al.
51	45.8	–	0.208	New Delhi, India	Kumar Jain et al.	104	–	29.53	0.498	Perlis, Malaysia	Ibrahim et al.
52	53	–	0.27	New Delhi, India	Kumar Jain et al.	105	–	28.19	0.335	Perlis, Malaysia	Ibrahim et al.
53	47.6	–	0.276	New Delhi, India	Kumar Jain et al.						

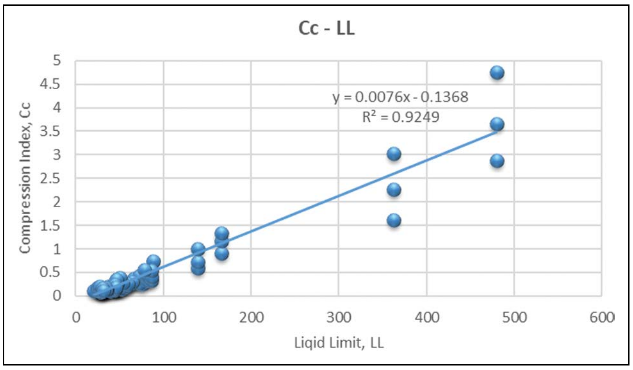

Figure 3. Observed Compression Index (C_c) and Liquid Limit (LL) with Linear Regression Analysis.

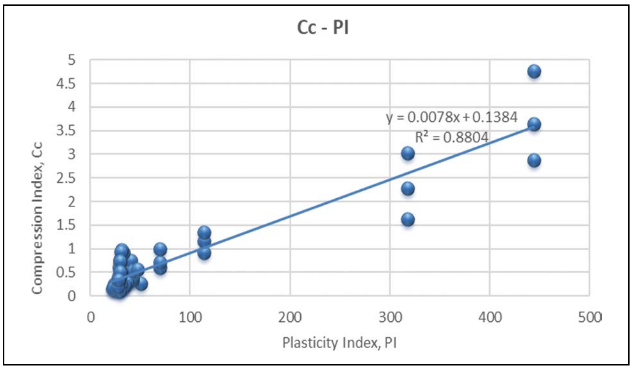

Figure 4. Observed Compression Index (Cc) and Plasticity Index (PI) with Linear Regression Analysis.

Table 2. Regression outputs between compression index, liquid limit, and plasticity index

Regression parameters	C_c-LL	C_c-PI
Multiple R	0.96170497	0.938300725
R Square	0.92487645	0.880408251
Observations	87	61

22.53% and 443.7%. The R-Square value of the correlation is 0.88, representing a solid relationship, as seen in Table 2.

$$(C_C=0.0076LL - 0.1368, R^2=0.9249) \quad (95)$$

$$(C_C=0.0078PI + 0.1384, R^2=0.8804) \quad (96)$$

According to Figures 3 and 4, it can be observed that for LL and PI values greater than 300, the correlation does not predict the Cc value, which can be due to the variable behavior of high plastic clayey soil and their swelling potential so restrictive criteria may be needed to be applied in the correlation. On the other hand, according to the studies presented in the literature, these parameters correlate well for low- plastic soils. Moreover, it can be concluded that the compression index values relate better with plasticity index values than shrinkage index and linear shrinkage values, respectively.

5. CONCLUSION

This study has studied and compared correlations between C_c and LL, C_c and PI, and C_C and w_n. According to the results, as shown in Table 2, the compression index strongly correlates with the liquid limit and plasticity index. As stated in the methodology section, the parameters considered suitable for estimating the compression index can be the primarily liquid limit and plasticity index. The purpose of the regression analysis in this study was to establish strong correlations with samples of various characteristics collected from independent studies. The obtained results presented correlations with strong R-square coefficients that support the studies in the literature. These parameters can support field data estimating the compression index under certain conditions. On the other hand, the coefficient of consolidation best correlates with the plastic index. In the absence of other test data, such as shrinkage limit and shrinkage index, which are not very prevalent tests, these findings can help engineers make predictions of different consolidation parameters with high accuracy without performing conventional oedometer tests.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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