The Estimation of Compaction Parameter Values Based on Soil Properties Values Stabilized with Portland Cement

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Abstract. The strength and durability of pavement construction is highly dependent on the properties and subgrade bearing capacity. This then led to the idea of the selection methods to estimate the density of the soil with the proper implementation of the system, fast and economical. This study aims to estimate the compaction parameter value namely the maximum dry unit weight ($\gamma_{d \max}$) and optimum moisture content ($w_{opt}$) of the soil properties value that stabilized with Portland Cement. Tests conducted in the laboratory of soil mechanics to determine the index properties (fines and liquid limit) and Standard Compaction Test. Soil samples that have Plasticity Index (PI) between 0-15% then mixed with Portland Cement (PC) with variations of 2%, 4%, 6%, 8% and 10%, each 10 samples. The results showed that the maximum dry unit weight ($\gamma_{d \max}$) and $w_{opt}$ has a significant relationship with percent fines, liquid limit and the per centation of cement. Equation for the estimated maximum dry unit weight ($\gamma_{d \max}$) = 1.782 - 0.011*LL + 0.000*F + 0.006*PS with $R^2 = 0.915$ and the estimated optimum moisture content ($w_{opt}$) = 3.441 + 0.594*LL + 0.025*F + 0.024*PS with $R^2 = 0.726$.

1. Introduction
Strength and durability of pavement construction is dependent on the soil properties and subgrade bearing capacity. Compaction is a treat that using to obtain a stable soil bearing capacity [1]. The parameter values obtained from the compaction experiment to obtain the maximum dry unit weight ($\gamma_{d \max}$) and optimum moisture content (Wopt).

In determining the value of the compaction parameters will need a lot of material, high cost for the testing, the expert operators in laboratory and taking a lot of times in laboratory. On the other side, the testing to determine an index value of subgrade material properties is not difficult, it does not need an expensive equipment and time for testing is also shorter [2]. If the results from the value of index properties can be used to predict the maximum dry unit weight and optimum water content of a subgrade material, obviously will be able to save time, energy and cost for the implementation process.

There was a research on the determination of the maximum dry weight of aggregate for subbase and research on the estimation of parameters compaction of aggregate for subgrade based on the data of index properties [3]. This study aims to estimate the parameters of compacting used for subgrade layer with Plasticity Index (PI) between 0-15%. By using the linear regression equation, the values of laboratory compaction parameter estimated (maximum dry unit weight and optimum water content) subgrade material mixed with Portland Cement based on the data of soil index properties (fines and liquid limit) and the addition of cement content[4].
2. Literature Reviews

Compaction is a process to pull out the air in the soil’s pores by mechanical method. Mechanical method that used to compact the soil can be used in various ways. In practice usually by grinding, but in laboratory by pounding using a proctor. The physical properties of the soil (index properties) showed the soil properties that indicate the type of soil (classification) and soil conditions and provides a connection to the mechanical properties (engineering properties) such as strength and compression or a tendency to inflate and permeability. The physical properties of the soil (index properties) include moisture content, density, Sieve Analysis, Atterberg Limit Test and others.

Several studies for estimating the value of soil compacting (maximum dry unit weight and optimum water content) has been developed. Research to determine the relation between the parameters of compaction, firstly done by Johnson and Sallberg (1962). Then followed by the study of Al-Khafaji (1993) and formulate the relation between the value of compacting with Atterberg Limits into an equation as follows:

For the soil in Irak,
\[
\begin{align*}
MDD & = 2.44 - 0.22PL - 0.008LL \\
OMC & = 0.24LL + 0.63PL - 3.13
\end{align*}
\] (1)
\] (2)

For the soil in America,
\[
\begin{align*}
MDD & = 2.27 - 0.19PL - 0.003LL \\
OMC & = 0.14LL + 0.54PL
\end{align*}
\] (3)
\] (4)

By the Boltz empiric Equation, et.al (1998), found an equation of linear relation between maximum dry unit weight by using compaction pounding. The result from correlation formulated in a linear equation as follows:

\[
\begin{align*}
MDD & = (2.27 \log LL - 0.94) \log E - 0.16LL + 17.02 \\
OMC & = (12.39 - 12.21 \log LL) \log E + 0.67LL + 9.21
\end{align*}
\] (5)
\] (6)

Then Ugbe (2012) suggested an equation to predict the maximum dry unit weight and optimum moisture content by using index properties value (fines percentage, liquid limit and specific gravity) with this equation:

\[
\begin{align*}
MDD & = 15.665SG + 1.526LL - 4.313F + 2011.960 \\
R^2 & = 0.895 \\
OMC & = 0.129F - 0.0196LL - 1.4233SG + 11.399 \\
R^2 & = 0.795
\end{align*}
\] (7)
\] (8)

3. Research Methods

The number of samples examined 50 samples with a range of values Plasticity Index (PI) between 0-15%. Then the sample is mixed with Portland Cement (PC) with a variation of 2%, 4%, 6%, 8% and 10%, 10 samples for each percentage. The general equation used in determining the regression equation is as follows: \( Y = aX + b \)

by: \( Y = \) maximum dry bulk density (\( \gamma_d \text{ max} \))/optimum moisture content (\( W_{\text{opt}} \)); \( X = \) index properties (fines/liquid limit) and the percent addition of cement; \( a = \) constant variable and \( b = \) variable.

If a strong relation is obtained for each variable then continued using two variables and then the three variables. The accuracy of the correlation between variables measured by the coefficient of determination \( (R^2) \) as listed in Table 1.
Table 1. Accuracy Coefficient Of Determination (R²)

| Values of R² | Accuracy          |
|--------------|-------------------|
| < 0.25       | Not Good          |
| 0.25 – 0.55  | Relatively Good   |
| 0.56 – 0.75  | Good              |
| > 0.76       | Very Good         |

Source: Kamarudin (2005)

4. Results And Analysis

4.1 Soil Laboratory Testing Results

Laboratory testing conducted is a test to determine the soil physical properties (index properties) that consist of Sieve Analysis, Atterberg Limits Test and Standard Compaction Test to gain compaction parameter values. The test results of soil samples are presented in table 2, while the statistical data shown in table 3.

Table 2. Testing Result of Soil Samples

| No | Soil Classification | AASHTO | USCS | Fines (%) | LL (%) | PL (%) | PI (%) | \(\gamma_d\) max (gr/cm³) | Wopt (%) |
|----|---------------------|--------|------|-----------|--------|--------|--------|------------------------|----------|
| 1  | A-4                 | SC     | 42.01| 27.20     | 18.65  | 8.55   | 1.462  | 21.23                  |
| 2  | A-4                 | CL     | 58.74| 29.37     | 20.08  | 9.29   | 1.423  | 22.67                  |
| 3  | A-6                 | CL     | 59.50| 29.62     | 18.60  | 11.02  | 1.421  | 22.74                  |
| 4  | A-4                 | SC     | 43.83| 26.60     | 17.77  | 8.83   | 1.466  | 20.98                  |
| 5  | A-4                 | SC-SM  | 40.41| 26.11     | 19.27  | 6.84   | 1.473  | 20.88                  |
| 6  | A-4                 | SC     | 48.77| 29.10     | 21.52  | 7.58   | 1.444  | 22.25                  |
| 7  | A-4                 | CL     | 50.90| 28.63     | 20.25  | 8.37   | 1.450  | 21.98                  |
| 8  | A-4                 | CL     | 51.39| 28.58     | 19.87  | 8.71   | 1.451  | 21.74                  |
| 9  | A-4                 | SC     | 40.33| 26.01     | 17.45  | 8.56   | 1.499  | 19.76                  |
| 10 | A-4                 | CL     | 59.94| 30.38     | 22.17  | 8.22   | 1.421  | 23.16                  |
| 11 | A-4                 | SC     | 45.70| 31.56     | 22.47  | 9.09   | 1.415  | 24.33                  |
| 12 | A-4                 | SC     | 39.81| 25.83     | 16.59  | 9.24   | 1.502  | 18.40                  |
| 13 | A-4                 | SC     | 46.04| 27.59     | 18.44  | 9.16   | 1.460  | 21.52                  |
| 14 | A-4                 | SC     | 46.03| 27.36     | 18.94  | 8.43   | 1.461  | 21.50                  |
| 15 | A-6                 | CL     | 51.81| 29.08     | 17.21  | 11.87  | 1.445  | 22.75                  |
| 16 | A-4                 | CL     | 62.17| 33.10     | 22.86  | 10.23  | 1.398  | 26.51                  |
| 17 | A-4                 | SC     | 44.58| 28.14     | 18.39  | 9.76   | 1.454  | 21.59                  |
| 18 | A-4                 | CL     | 51.77| 29.04     | 20.17  | 8.87   | 1.446  | 22.24                  |
| 19 | A-4                 | SC     | 44.55| 27.86     | 19.81  | 8.05   | 1.459  | 21.55                  |
| 20 | A-4                 | SC     | 44.64| 28.49     | 19.65  | 8.84   | 1.451  | 21.98                  |
| 21 | A-4                 | SC     | 43.33| 26.69     | 17.76  | 8.94   | 1.478  | 20.44                  |
| 22 | A-4                 | SC     | 46.02| 27.55     | 18.13  | 9.42   | 1.466  | 21.91                  |
| 23 | A-4                 | CL     | 59.54| 28.22     | 18.19  | 10.03  | 1.421  | 22.90                  |
| 24 | A-4                 | CL     | 59.81| 30.50     | 21.43  | 9.07   | 1.422  | 23.50                  |
| 25 | A-4                 | SC     | 44.62| 28.34     | 19.71  | 8.63   | 1.453  | 21.16                  |
| 26 | A-4                 | CL     | 59.83| 30.25     | 21.13  | 9.12   | 1.426  | 23.20                  |
| 27 | A-4                 | SC     | 43.03| 25.52     | 17.11  | 8.41   | 1.495  | 18.32                  |
| 28 | A-4                 | SC     | 49.72| 28.82     | 20.22  | 8.60   | 1.447  | 22.75                  |
| 29 | A-6                 | CL     | 61.66| 32.02     | 21.02  | 11.00  | 1.415  | 25.65                  |
Table 3. The Statistic of Soil Samples Testing Result

| No | Soil Classification | Fines (%) | LL (%) | PL (%) | PI (%) | $\gamma_{d \text{ max}}$ (gr/cm$^3$) | Wopt (%) |
|----|---------------------|----------|--------|--------|--------|----------------------------------|----------|
| 31 | A-4 CL              | 51.95    | 28.72  | 20.39  | 8.33   | 1.448                            | 22.24    |
| 32 | A-4 CL              | 57.79    | 29.34  | 21.12  | 8.23   | 1.439                            | 23.96    |
| 33 | A-4 SC              | 47.52    | 28.04  | 18.74  | 9.30   | 1.458                            | 22.55    |
| 34 | A-4 SC              | 48.91    | 26.83  | 17.77  | 9.05   | 1.445                            | 22.07    |
| 35 | A-4 CL              | 59.83    | 30.19  | 20.51  | 9.68   | 1.427                            | 23.26    |
| 36 | A-4 CL              | 61.82    | 33.11  | 21.72  | 11.39  | 1.384                            | 24.48    |
| 37 | A-4 CL              | 57.70    | 29.35  | 19.62  | 9.73   | 1.439                            | 22.91    |
| 38 | A-4 CL              | 51.74    | 29.00  | 19.23  | 9.77   | 1.440                            | 21.25    |
| 39 | A-4 SC              | 49.84    | 29.47  | 19.76  | 9.72   | 1.437                            | 23.25    |
| 40 | A-4 CL              | 57.84    | 29.51  | 19.85  | 9.66   | 1.437                            | 22.35    |
| 41 | A-4 CL              | 51.78    | 29.08  | 20.79  | 8.29   | 1.442                            | 22.60    |
| 42 | A-4 SC              | 48.69    | 28.63  | 20.30  | 8.33   | 1.449                            | 22.13    |
| 43 | A-4 CL              | 59.84    | 31.01  | 22.03  | 8.98   | 1.421                            | 24.05    |
| 44 | A-6 CL              | 61.77    | 32.75  | 21.10  | 11.66  | 1.390                            | 25.20    |
| 45 | A-4 CL              | 51.89    | 29.04  | 19.96  | 9.08   | 1.443                            | 23.38    |
| 46 | A-4 CL              | 57.84    | 29.37  | 20.22  | 9.16   | 1.439                            | 21.89    |
| 47 | A-4 SC              | 44.86    | 28.56  | 19.75  | 8.81   | 1.450                            | 23.17    |
| 48 | A-4 CL              | 57.79    | 29.31  | 19.67  | 9.64   | 1.440                            | 22.67    |
| 49 | A-4 SC              | 48.64    | 28.86  | 20.42  | 8.43   | 1.446                            | 22.79    |
| 50 | A-4 CL              | 57.78    | 29.58  | 19.77  | 9.82   | 1.436                            | 22.26    |

Maximum dry unit weight; Wopt = Optimum water content; Fines = Fines percentage; LL = Liquid Limit; PL = Plastic Limit dan PI = Plasticity Index

4.2 Soil + Cement Laboratory Testing Results
After the soil mixed with cement, then make a test with soil samples without cement. The test results of soil samples plus cement are presented in table 4, while the statistical data given in table 5.
Table 4. Testing Results of Soil Samples + Cement

| No | PS (%) | Fines (%) | LL (%) | PL (%) | PI (%) | $\gamma_{d \max}$ (gr/cm³) | Wopt (%) |
|----|--------|-----------|--------|--------|--------|---------------------------|----------|
| 1  | 2      | 42.34     | 26.67  | 19.00  | 7.66   | 1.465                     | 20.60    |
| 2  | 2      | 58.89     | 30.00  | 20.02  | 8.98   | 1.425                     | 22.07    |
| 3  | 2      | 60.11     | 29.44  | 18.72  | 10.72  | 1.424                     | 22.17    |
| 4  | 2      | 44.14     | 26.13  | 18.08  | 8.05   | 1.469                     | 20.36    |
| 5  | 2      | 41.06     | 25.62  | 19.60  | 6.02   | 1.476                     | 20.25    |
| 6  | 2      | 49.03     | 28.87  | 21.81  | 6.86   | 1.446                     | 21.63    |
| 7  | 2      | 51.72     | 28.09  | 20.62  | 7.48   | 1.453                     | 21.40    |
| 8  | 2      | 51.65     | 28.04  | 20.23  | 7.81   | 1.454                     | 21.14    |
| 9  | 2      | 40.85     | 25.49  | 17.80  | 7.69   | 1.503                     | 19.24    |
| 10 | 2      | 60.42     | 29.85  | 22.51  | 7.35   | 1.424                     | 22.71    |
| 11 | 4      | 47.90     | 30.57  | 23.13  | 7.43   | 1.428                     | 23.43    |
| 12 | 4      | 41.89     | 24.88  | 17.23  | 7.65   | 1.520                     | 17.58    |
| 13 | 4      | 47.75     | 26.62  | 19.08  | 7.54   | 1.475                     | 20.64    |
| 14 | 4      | 47.76     | 26.24  | 19.68  | 6.57   | 1.478                     | 20.76    |
| 15 | 4      | 53.10     | 28.59  | 17.53  | 11.06  | 1.460                     | 22.11    |
| 16 | 4      | 64.59     | 32.51  | 23.26  | 9.25   | 1.414                     | 25.70    |
| 17 | 4      | 46.30     | 27.47  | 18.82  | 8.66   | 1.469                     | 20.81    |
| 18 | 4      | 53.54     | 28.03  | 20.85  | 7.18   | 1.464                     | 21.43    |
| 19 | 4      | 47.02     | 26.76  | 20.54  | 6.22   | 1.474                     | 20.72    |
| 20 | 4      | 46.42     | 27.46  | 20.34  | 7.12   | 1.469                     | 21.09    |
| 21 | 6      | 47.37     | 25.00  | 18.87  | 6.13   | 1.507                     | 19.38    |
| 22 | 6      | 49.22     | 26.10  | 19.10  | 6.99   | 1.497                     | 20.82    |
| 23 | 6      | 62.54     | 27.12  | 18.93  | 8.19   | 1.449                     | 21.98    |
| 24 | 6      | 63.14     | 28.96  | 22.45  | 6.51   | 1.454                     | 22.43    |
| 25 | 6      | 49.18     | 26.73  | 20.82  | 5.91   | 1.484                     | 20.05    |
| 26 | 6      | 64.11     | 28.76  | 22.12  | 6.64   | 1.460                     | 22.14    |
| 27 | 6      | 47.57     | 23.74  | 18.30  | 5.44   | 1.548                     | 17.04    |
| 28 | 6      | 54.66     | 27.04  | 21.40  | 5.64   | 1.478                     | 21.69    |
| 29 | 6      | 65.39     | 31.03  | 21.68  | 9.35   | 1.441                     | 24.67    |
| 30 | 6      | 54.90     | 27.56  | 21.10  | 6.46   | 1.474                     | 21.36    |
| 31 | 8      | 57.71     | 26.61  | 21.79  | 4.83   | 1.490                     | 20.92    |
| 32 | 8      | 63.09     | 27.08  | 22.61  | 4.47   | 1.482                     | 22.59    |
| 33 | 8      | 53.82     | 26.17  | 19.99  | 6.18   | 1.504                     | 21.26    |
| 34 | 8      | 54.44     | 25.02  | 18.99  | 6.03   | 1.492                     | 20.76    |
| 35 | 8      | 65.24     | 28.35  | 21.73  | 6.62   | 1.470                     | 21.99    |
| 36 | 8      | 67.30     | 31.90  | 22.52  | 9.38   | 1.424                     | 22.27    |
| 37 | 8      | 63.55     | 27.56  | 20.82  | 6.74   | 1.485                     | 21.60    |
| 38 | 8      | 56.23     | 27.19  | 20.44  | 6.75   | 1.491                     | 19.95    |
| 39 | 8      | 55.80     | 27.39  | 21.13  | 6.26   | 1.489                     | 21.50    |
| 40 | 8      | 62.71     | 27.58  | 21.13  | 6.45   | 1.487                     | 20.97    |
| 41 | 10     | 58.59     | 26.23  | 21.70  | 4.54   | 1.503                     | 21.04    |
| 42 | 10     | 55.90     | 25.70  | 22.26  | 3.44   | 1.513                     | 20.46    |
| 43 | 10     | 66.56     | 28.06  | 23.99  | 4.07   | 1.483                     | 22.41    |
| 44 | 10     | 68.42     | 31.35  | 22.03  | 9.32   | 1.448                     | 22.71    |
by: $\gamma_{d \text{ max}} = \text{Maximum dry unit weight}$; $W_{\text{opt}} = \text{Optimum water content}$; $\text{Fines} = \text{Fines percentage}$; $LL = \text{Liquid Limit}$; $PL = \text{Plastic Limit}$, $PI = \text{Plasticity Index}$ and $PS = \text{Percentage of cement addition}$

### Table 5. The Statistic of Soil Samples + Cement Testing Results

| Variabel                           | Range         | Average |
|-----------------------------------|---------------|---------|
| Fines Percentage (%)              | 40.85 – 68.42 | 55.25   |
| Liquid Limit (%)                  | 23.74 – 32.51 | 27.46   |
| Maximum dry unit weight (gr/cm$^3$) | 1.414 – 1.548 | 1.476   |
| Optimum water content (%)         | 17.04 – 25.70 | 21.28   |

$N = 50$

The next step is make statistic analysis to determine the correlation between compaction parameters with a value of index properties and the addition of cement. The values of index properties used is the percent of fine grains (fines) and Liquid Limit (LL). The regression relation using one variable and two variables were analysed with Microsoft Excel program 2007 while the regression relation using three variables were analysed with SPSS version 16. The linear regression models were used to determine the relation between compaction parameters with the value of index properties and the addition of cement.

#### 4.3 The Relation Between Compaction Parameter Value with Index Properties

By using regression method to determine the relation between compaction parameter values with index properties and the addition of cement, obtained an equations by using Microsoft Excel and SPSS. The equations that form is as follows:

1. Relationship between the maximum dry unit weight ($\gamma_{d \text{ max}}$) with fine grains percent (fines) are:
   \[
   (\gamma_{d \text{ max}}) = 1.527 - 0.000 \times \text{Fines} \quad (9)
   \]
   \[
   R^2 = 0.062
   \]
   This means that 6.2% of maximum dry unit weight values can be estimated using linear equations of fine grains percent value.

2. Relation between maximum dry unit weight ($\gamma_{d \text{ max}}$) with Liquid Limit (LL) are:
   \[
   (\gamma_{d \text{ max}}) = 1.855 - 0.013 \times \text{LL} \quad (10)
   \]
   \[
   R^2 = 0.739
   \]
   This means that 73.9% of the maximum dry unit weight values can be estimated using linear equations of the value of the liquid limit.

3. Relation between maximum dry unit weight ($\gamma_{d \text{ max}}$) with the addition of cement percent are:
   \[
   (\gamma_{d \text{ max}}) = 1.443 + 0.005 \times \text{PS} \quad (11)
   \]
   \[
   R^2 = 0.276
   \]
   This means that 27.6% of dry weight of the maximum dry unit weight value can be estimated using linear equations of the value of percent cement addition.

4. Relation between optimum water content ($W_{\text{opt}}$) with fine grains percent (fines) are:
   \[
   W_{\text{opt}} = 15.371 + 0.106 \times \text{Fines} \quad (12)
   \]
   \[
   R^2 = 0.347
   \]
   This means that 34.7% moisture content optimum value can be estimated using linear equations of fine grains percent value.
5. Relation between optimum water content (Wopt) with liquid limit (LL) are:

\[ W_{opt} = 3.504 + 0.647 \times LL \]  
\[ R^2 = 0.701 \]  
This means that 70.1% moisture content optimum value can be estimated using linear equations of the liquid limit value.

6. Relationship optimum water content (Wopt) with the addition of cement percent are:

\[ W_{opt} = 21.223 + 0.009 \times PS \]  
\[ R^2 = 0.000 \]  
This means that the 0% value optimum moisture content can be estimated using a linear equation of a percent cement additional value.

Then combined the relation between compaction parameter values using two variables index properties and percent cement addition as follows:

1. Relation between the maximum dry unit weight (\( \gamma_{d \ max} \)) with fine grains percent (fines) and Liquid Limit (LL) are:

\[ (\gamma_{d \ max}) = 1.867 + 0.001 \times \text{fines} - 0.017 \times LL \]  
\[ R^2 = 0.812 \]  
This means that 81.2% of maximum dry unit weight value can be estimated using multiple linear equation of fines percent and liquid limit value.

2. Relation between the maximum dry unit weight (\( \gamma_{d \ max} \)) with fine grains percent (fines) and percent cement addition (PS) are:

\[ (\gamma_{d \ max}) = 1.588 - 0.003 \times \text{fines} + 0.011 \times \text{PS} \]  
\[ R^2 = 0.743 \]  
This means that 74.3% of maximum dry unit weight value can be estimated using multiple linear equation of fine grains percent value and the percent of cement addition.

3. Relation between the maximum dry unit weight (\( \gamma_{d \ max} \)) with Liquid Limit (LL) and the percent of cement addition (PS) are:

\[ (\gamma_{d \ max}) = 1.804 - 0.013 \times LL - 0.004 \times PS \]  
\[ R^2 = 0.905 \]  
This means that 90.5% of maximum dry unit weight value can be estimated using multiple linear equation of fine grains percent value and the percent of cement addition.

4. Relation between optimum water content (Wopt) with fine grains percent (fines) and Liquid Limit (LL) are:

\[ W_{opt} = 3.813 + 0.033 \times \text{fines} + 0.569 \times LL \]  
\[ R^2 = 0.725 \]  
This means that 72.5% water content optimum value can be estimated using multiple linear equation of fines percent value and liquid limit.

5. Relation between optimum water content (Wopt) with fine grains percent (fines) and percent of cement addition (PS) are:

\[ W_{opt} = 13.974 + 0.159 \times \text{fines} - 0.244 \times \text{PS} \]  
\[ R^2 = 0.507 \]  
This means that 50.7% of the value of the optimum water content can be estimated using multiple linear equation of fines percent value and percent of cement addition.

6. Relation optimum water content (Wopt) with liquid limit (LL) and the percent of cement addition (PS) are:

\[ W_{opt} = 2.652 + 0.663 \times LL + 0.070 \times \text{PS} \]  
\[ R^2 = 0.721 \]  
This means that 72.1% moisture water optimum value can be estimated using multiple linear equation of liquid limit and percent of cement addition.

From the results of multiple linear regression known that the relation between the value of compaction parameters with a combination of two variables of percent fine grains (fines), Liquid Limit (LL) and the percent of cement addition (PS) is strong enough. It can be seen from the value of \( R^2 \). With \( R^2 \) model which in good category can get the relation with three variables to estimate the maximum dry
unit weight and optimum water content. Relations between compaction parameter values using three variables are as follows:

1. For maximum dry bulk density values are:
   \[
   (\gamma_{d \text{ max}}) = 1.782 - 0.011 \times \text{LL} + 0.000 \times \text{Fines} + 0.006 \times \text{PS} \tag{21}
   \]
   \[R^2 = 0.915\]
   This means that 91.5\% maximum dry unit weight can be estimated with a range of 95\% using a variable of liquid limit, percent fines, and the percent of cement addition.

2. For optimum water content values are:
   \[
   W_{\text{opt}} = 3.441 + 0.594 \times \text{LL} + 0.025 \times \text{Fines} + 0.024 \times \text{PS} \tag{22}
   \]
   \[R^2 = 0.726\]
   This means that 72.6\% optimum moisture content can be predicted with a range of 95\% using a variable of liquid limit, percent fines, and the percent of cement addition.

Figure 1 and figure 2 show the correlation of estimated maximum dry unit weight with actual maximum dry unit weight and estimated optimum water content with the actual optimum water content. From the equation obtained that level of accuracy showed by the value of \(R^2 = 91.5\%\) and 72.6\%. With a value of \(R^2\) show that the equations using three independent variable, and they are the percent fines, liquid limit and percent addition of cement can be used in estimating the value of the parameter compaction.

![Figure 1](image_url)

**Figure 1.** Relation Graphic of the actual maximum dry unit weight with the estimated maximum dry unit weight.
5. Conclusion
From the results of laboratory testing and analysis of data obtained following matters:
1. Statistical analysis using linear equations can be used in estimating the value of the parameter compaction.
2. The maximum dry unit weight (γd max) and Wopt has a significant relation to the percent of fines, the liquid limit and the percent of cement addition.
3. The equations that have resulted from this research has an excellent safety range for maximum dry unit weight and also for the optimum water content. This can be proof from the R² value generated.

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