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Electrical Density Gauge, A Device for Quick Quality Control of Soil Compaction - Case Study in Indonesia

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Abstract

Soil compaction is a fundamental process in major civil engineering works such as road embankments, earth fill dams, and airport constructions. During the construction phase, soil is compacted in successive layers, and the quality of each layer is evaluated by the ratio of its dry density to the maximum dry density as determined by the Proctor compaction test. Conventional methods for measuring soil compaction, such as the sand cone and rubber balloon techniques, are widely used but can pose limitations for quick construction projects due to their time-consuming nature. In response to this, the Complex Impedance Measuring Instrument (CIMI), commonly referred to as the Electrical Density Gauge (EDG), has recently been introduced in Indonesia. This method offers a quick quality control of field compaction by applying a direct current (DC) through a specific soil layer, yielding results within minutes. The EDG requires calibration through the development of a soil model, which involves inputting a set of the soil's physical and electrical properties. Following calibration, the soil's physical properties in the field can be estimated by applying an electric current. Although this technique has been adopted in numerous countries, its implementation in Indonesia remains limited. This study aims to evaluate the performance of the Electrical Density Gauge (EDG) and explore its potential for broader application in Indonesia. Three distinct soil types sourced from different quarries were examined. Each soil type, at varying moisture contents, was compacted using different energy levels into concrete molds measuring 40 cm in diameter and 30 cm in height, serving as a modified version of the standard Proctor mold. A total of 15 tests were performed to compare results obtained from the EDG with those from the traditional sand cone method. Statistical analysis was conducted using Mean Absolute Error (MAE) and the coefficient of determination (R^2). The findings indicate that the EDG performs reliably in measuring both soil moisture content and dry density.

1. Introduction

Soil compaction can be a main civil works especially in construction of road embankment, earth fill dam, airport, etc. During the construction, soil is compacted layer by layer and the quality of each layer is strictly controlled by a ratio between dry density of the compacted soil in the field and a maximum dry density of the same soil obtained from a Proctor test in the laboratory. This parameter is called relative compaction, more commonly stated by geotechnical engineers as "compaction". The test is immediately conducted after compaction by measuring the moisture content and unit weight of soil. A very common conventional method of this measurement is sand cone or rubber balloon method using 24 hours oven drying method (ASTM D2216), and of course this can be a constraint for a rapid project.

To overcome this situation, some quick methods have been recognized and utilized such as Nuclear Density Gauge (NDG), Electrical Impedance Spectroscopy (EIS), Capacitance Probes (CP), and Electrical Density Gauge (EDG) [1]. Each device has the advantage/disadvantages, and according the study, NDG has been the most popular testing of field soil compaction [2]. Since being used for the first time in the 1950s, some of the early publications regarding the use of NDG is reported in the 1960s [3], [4], and [5]. Since then, many considerable studies on this device were increasing across the world. A brief literature review of NDG performance has been reported and conclude that there are still some drawbacks and disadvantages of this method especially regarding the health and environmental safety issues as it uses hazardous radioactive materials if it is improperly operated [6]. This situation prompts the engineers to turn attention to using a better environmentally friendly method, and the EDG seems to be one of the best choices.

EDG was firstly proposed as one of the alternatives in-situ soil density measurement. It was patented in USA in 2005 by a group of inventors to provide a non-nuclear, portable, and low-cost device for measuring dry density of soil [7]. It is a quick non-destructive method operating simply by giving a DC electric current through a particular soil layer using a concept of complex impedance measuring instrument (CIMI). Lifecycle cost analysis associated with owning, operating, and maintaining has been conducted to evaluate the cost effectiveness of a particular project in USA indicating that EDG shows substantially lower cost compared to NDG [8]. Some other studies have also been conducted on EDG by many researchers using different approach including calibration method, type of soil, number of tests, temperature effect, etc [9], [10], [11] and [12]. The results indicating that the device has become the promising portable device offering easy to handle, quick, non-hazardous, and relatively low cost. A brief information regarding the methods will be presenting in the following section.

EDG has been utilized in many countries acrossthe world for their projects. However, since the inventory around 20 years ago, this method is not well recognized in Indonesia. So far, there is no report regarding the study of EDG and its utilization in the country. This paper presents the preliminary result of the EDG in a Sumatera toll road project. The study was conducted using three different soilsfrom three different quarries. A new approach of energy variation of compaction with the variation of moisture content representing dry side, optimum, and wet side of laboratory Proctor characteristic curve. The larger Proctor-like concrete mold was introduced offering a simple procedure for developing soil model.

2. Electrical Density Gauge

EDG works by transmitting an electric current from a set of metal probes embedded to a particular depth of soil layer. Soil dielectric properties are specific to a soil physical property, and are measured as capacitance and resistance. Variation of a specific soil types would have a variation of their dielectric properties. This principle is adopted by EDG to develop a soil model as a mathematical expression containing the relationship of set of information. In other word, it is a calibration to relate physical properties of soil (moisture content and density) and its dielectric properties. The more information of physical and dielectric properties the better soil model is constructed. Once a soil model is built in the EDG system, the moisture content and density of a particular soil would be obtained immediately simply by transmitting an electric current through its probes. Fig.1 shows the illustration of the principles of EDG.

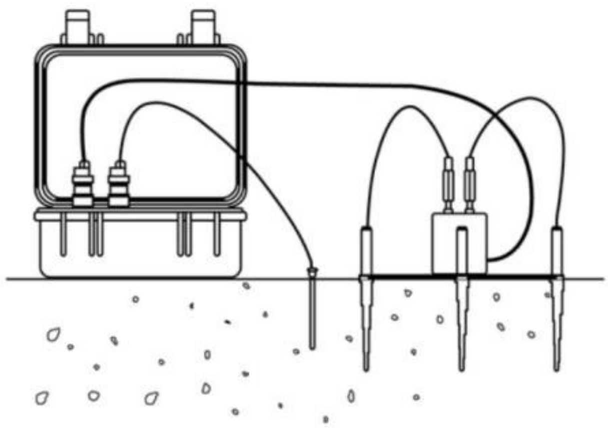

Fig. 1 *Principle of EDG according to ASTM D7698-11a (D18 Committee 2011)*

Soil modeling of EDG is a process of a solving of two equations. The first equation is relating between soil bulk density and its electric impedance, whereas the second one is relating the weight of water per unit volume and the quotient of capacitance and resistance as presented in the following equations:

$$\gamma_m = b_1 + Z_s m_1 \quad (1)$$

$$W_w = b_2 + \left(\frac{C_s}{R_s}\right) m_2 \quad (2)$$

Where γ_m is bulk density, W_w is weight of waterper unit volume, Z_s is soil impedance, C_s is soil capacitance, R_s is soil resistance, b_1 and b_2 intercept, and m_1 dan m_2 is slope of the equations.

During construction a soil model, EDG probes and sand cone devices are placed on a same soil surface area. Practically, EDG probes are firstly placed on that surface for collecting soil dielectric properties. It is then continued by collecting soil physical properties using sand cone method on the same place or very near to the EDG probes. The data from sand cone test is then inputted to the EDG.This situation is illustrated in Fig 2.

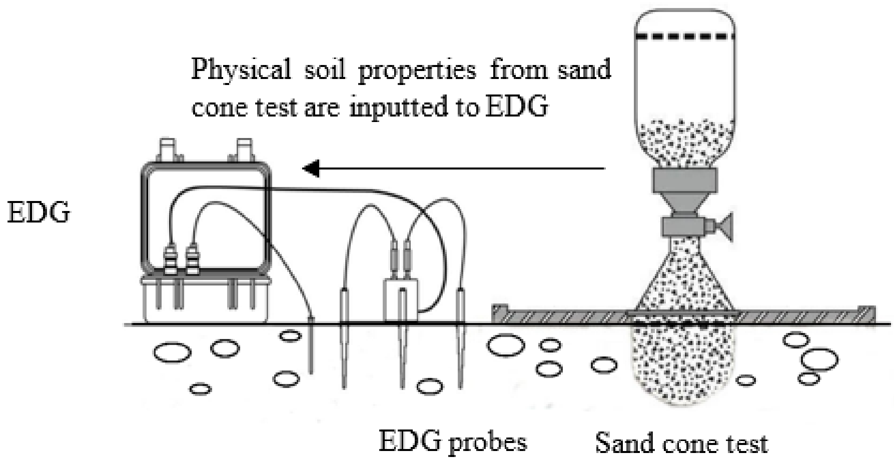

Fig. 2 *Collecting dielectric and soil properties for soil model*

3. Method

3.1 Location of the Study

The study was conducted to support the project of Sumatra Toll Road. A huge number of soil compaction works are required as almost every section of road was constructed on compacted soil. Soil laboratory was in Gebang Sub District, Langkat, the province of North Sumatera, Indonesia (Fig 3)

Fig. 3 *Research location*

3.2 Soil Preparation

Soil samples were taken from three quarries from different locations: Buluh Telang (BU), Serapu (SE), and Petronesia (PE) as those soils have been approved by the authorities to be utilized as fill materials for road embankment. The index properties test was then conducted to obtain gradation, consistency limits, and soil classification.At the same time, laboratory compaction test was also conducted to obtain Proctor compaction curve (optimum moisture content and dry density). Table 1 and Fig. 4 show the result of index properties and Proctor compaction result.

Table 1 *Index properties and proctor compaction result*

Soil Property	Quarry		
	BU	**SE**	**PE**
Gs	2.64	2.66	2.65
Gravel (%)	1.59	0.48	2.34
Sand (%)	48.91	62.11	65.08
Silt/clay (%)	49.50	37.41	32.58
LL (%)	28.00	22.23	33.13
PL (%)	17.74	12.23	21.70
PI (%)	10.26	10.00	11.43
Soil class (USCS)	SC	SC	SM
MDD (gr/cm^3)	1.695	1.88	1.74
OMC (%)	19.00	13.36	16.80

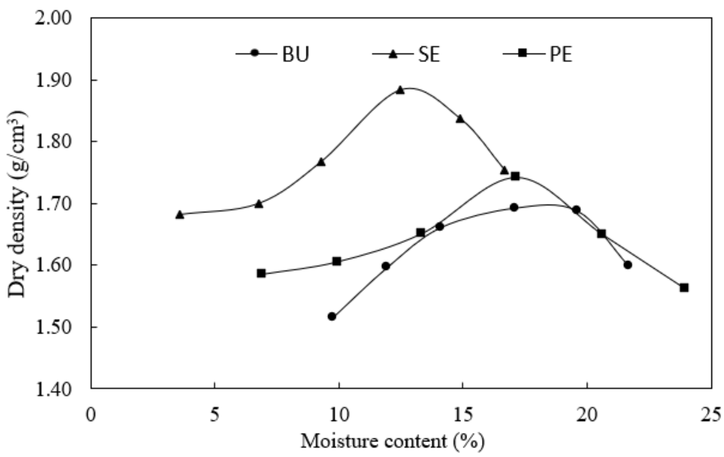

Fig. 4 *Proctor compaction curves*

3.3 Concrete Mold

One of the crucial steps of the compaction test using EDG is generating a of soil model to represent the relation between soil electrical properties and itsmoisture content and density. Firstly, EDG requiresdata of moisture content and density of compacted soil from other method such as from sand cone method. The size of mold must be modified to be fitwith the size of base plate of EDG. In this study, 3 concrete molds with the diameter of 40 cm and height of 30 cm were made as modification from steel Standard Proctor mold (diameter of 10.5 cm and height of 11.5 cm) as shown in Fig. 5.

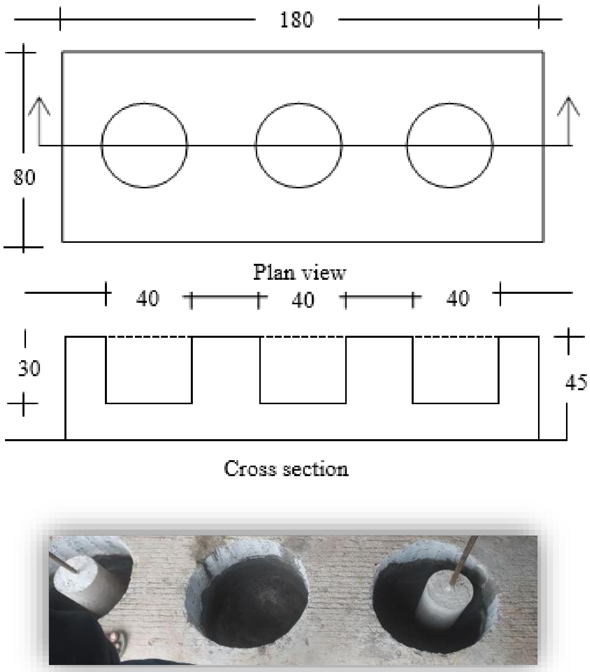

Fig. 5 *Concrete mold sketch for EDG soil model*

3.4 Construction of Soil Model

Briefly, soil model was constructed in three stages; soil compaction, measurement of dielectric properties by EDG, and sand cone test. Compaction of soil was conducted in laboratory using three molds as described in Section 3.2. Soil sample from a quarry was compacted to have a variation of targeted moisture content in dryside (OMC – 5%), optimum, and wet side (OMC +5%) of a Standard Proctor Compaction curve. Compaction energy was also varied to 50%, 100%,and 120% of Proctor compaction (594 kN-m/m^3). These variations were made to generate a wide spectrum of water content and density (the higher the energy, the denser the compacted soil). The illustration of variation of compacted soil is shownin Fig. 6.

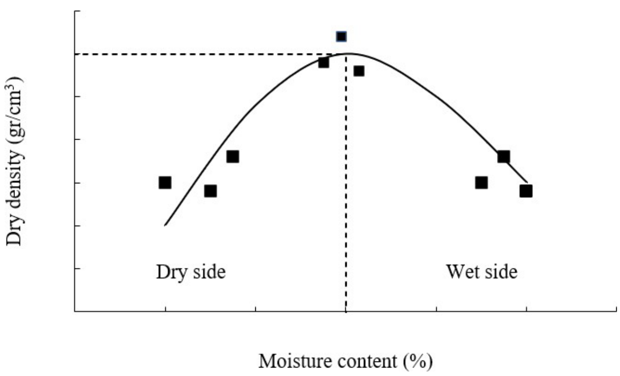

Fig. 6 *Illustration of soil compaction in variation of moisture content and density*

The measurement of soil dielectric propertieswas then conducted. EDG was placed on the compacted soil surface and record the electrical read out displayed on the screen. This stage was carried out for every single of compacted soil with moisture content and density. Soil model has not generated yet at this stage. The EDG needs the realmoisture content, density, and maximum drydensity from sand cone test. Moisture content was obtained using oven drying method, whereas density was obtained from sand cone measurement.Note that the sand cone test on a particular compacted soil was conducted immediately after EDG test on it. Once moisture content and density from sand cone was obtained, these data were then inputted on EDG and a soil model was generated. Some other similar tests were conducted for anothervariation of moisture content and density.

3.5 EDG and Sand Cone Measurement

After soil model has been generated, the performance of EDG was tested. In this study four parameters were investigated: moisture content, bulk density, dry density, and compaction. Conventional method of sand cone test with 24 hours oven drying method were adopted. Most of the tests were conducted in laboratory, and a few tests were also performed in the field.

Some soil sample from a quarry with a certain water content that previously been prepared was then compacted using concrete mold. After targeted compaction energy has been achieved, the ADG test was started. It was initially performed by placing EDG plate on the surface of the compacted soil, followed by penetrating four EDG probes into the soil, and giving electric current through these probes (Fig. 7a). Digital readout was then displayedon EDG screen. The data of moisture content, bulkdensity, dry density, and compaction were then automatically obtained. The process of EDG test forin situ was also performed directly on compacted soil in the field. Immediately after EDG test, the density of soil was also measured on the same placeusing sand cone method (Fig. 7b).

(a)

(b)

Fig. 7 *Test performed in the same place (a) EDG tests; (b) Sand cone test*

3.6 Mean Absolute Error

The measurement of error of an observed variable against its reference variable can be calculated by means of Mean Absolute Error (MAE). It is expressed as:

$$MAE = \frac{\sum_{i=1}^{n} |X - Yi|}{n} \quad (3)$$

Where *Xi* a parameter from EDG measurement, *Yi* is a parameter from sand cone test (as a reference), and n is number of sample. The value of R^2 explains how extent the variance of first variable influence to another variable.

4. Result

The performance of EDG was investigated using three soil samples from three different quarries. Based on Unified Soil Classification System, the first two samples are classified as clayey sand (SC) and the third as silty sand (SM).

4.1 Soil Model

Soil model was constructed based on its quarry.One soil model represents one quarry. Table 2 shows the input data for EDG obtained from sand cone test in laboratory. Variation of bulk density and moisture content representing dry side, OMC, and wet side of Proctor test for quarry of Bulu Telang. The input data from quarry of Serapu and Petronesia are not presented.

Table 2 *Soil model of Bulu Telang quarry*

⍰$_b$ *(gr/cm³)*	**Moisture content** *(%)*	**Note**
2.01	16.48	
2.06	16.91	OMC
2.02	16.61	
1.96	12.46	
1.88	11.36	-5% OMC
1.85	11.21	
2.01	21.68	
1.88	22.16	+5%OMC
1.99	22.94	

4.2 EDG Versus Sand Cone Test Result

The results of 15 EDG and sand cone tests arepresented in the following Figures (Fig. 8 – Fig. 11).Fig. 8 shows the variation of moisture content from EDG measurement indicating a pattern up anddown. The similar pattern is also indicated by the result from sand cone test. It shows that most of moisture content from EDG are relatively higher than that from sand cone test (13 from 15 tests). It can be concluded that EDG measurement of moisture content is quite consistent.

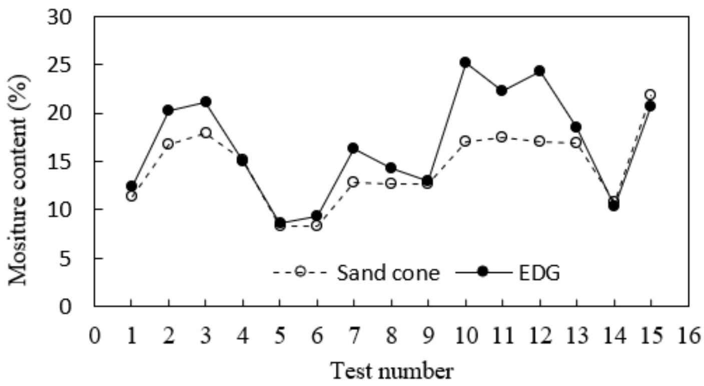

Fig. 8 *Moisture content from EDG vs sand cone tests*

Fig. 9 shows the result of bulk density measurement. The increase and decrease in bulk density obtained from EDG is not consistent with that sand cone test result; 8 of 15 data of the EDG result indicating higher value than that from sand cone tests. However, the pattern of increasing and decreasing is quite consistent. This situation is alsosimilar to the result of dry density as well as compaction (Rc) as shown in Fig. 10 and Fig 11 respectively.

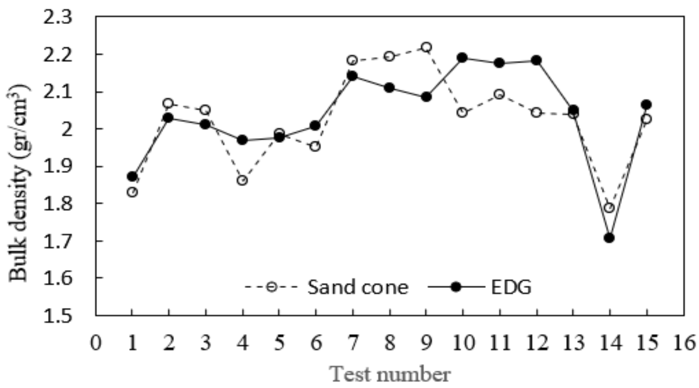

Fig. 9 *Bulk density from EDG vs sand cone method*

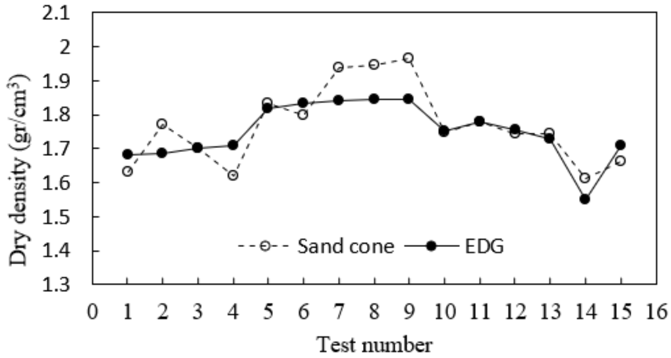

Fig. 10 *Dry density from EDG vs sand cone method*

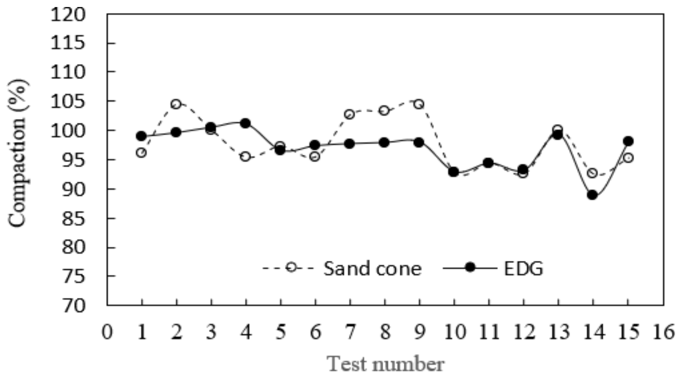

Fig. 11 *Compaction (Rc) from EDG vs sand cone method*

5. Discussion

The analysis was conducted to investigate the quality of EDG performance compared to sand cone test. Two approaches were utilized; 1) using coefficient of correlation, (R^2) and 2) using mean absolute error (MAE) analysis. Two parametershave a good correlation when it has R^2 near 1. The higher the R^2, the stronger the correlation. Lower MAE indicates that there is not much difference between compared variables. Four parameters are being investigated; moisture content (w), bulk density (γ_b), dry density (γd), and compaction (Rc).

Fig. 12 shows the scatter of moisture content data from EDG (abscissa) and sand cone method (ordinate). The range of moisture content obtained from EDG is 8.63 % - 25.11 % whereas the result from sand cone test is 8.38 % – 21.85 %. It can be observed that the data are relatively close to the straight line, using liner regression with the R2 value is 0.7645. It indicates that the difference between moisture content from EDG and sand cone test quite small. By using Eq (3), the error of this difference (MAE) is 2.54 %.

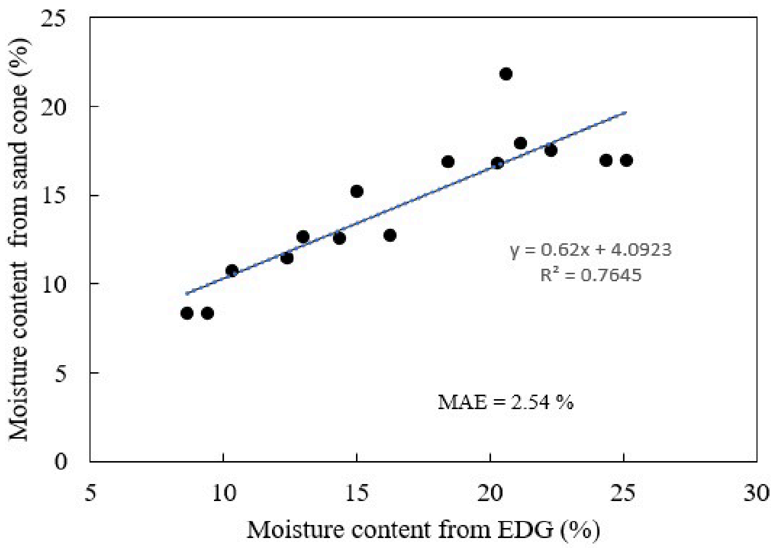

Fig. 12 *The scattered data of moisture content*

Fig. 13 – Fig. 15 shows the scattered data of bulk density (γb), dry density (γd) and compaction (Rc) data from EDG as well as from sand cone test.

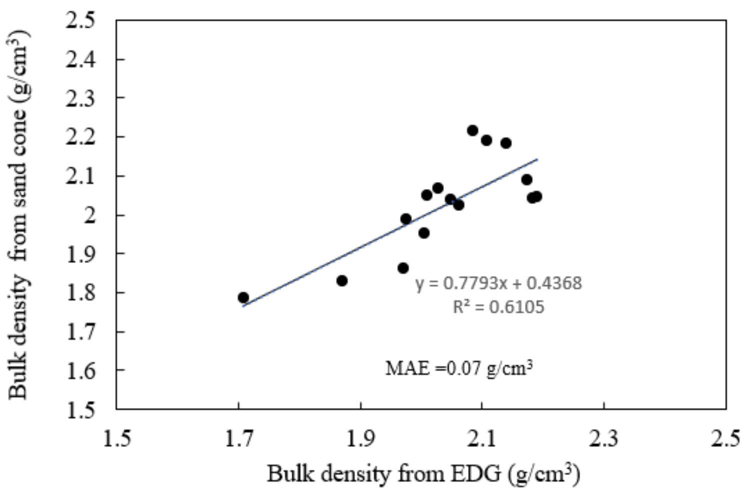

Fig. 13 *The scattered data of bulk density*

Fig. 13 shows that bulk density data are more widely scattered. Linear regression analysis shows that the value of R2 is 0.6105, indicating that in term of bulk density, the difference between EDG and sand cone is relatively not small. Error analysis using Eq. 3 shows that the value of MAE is 0.07 g/cm3. The similar result for dry density is presented in Fig. 14 showing the value of R2 is 0.7228 and the mean absolute error MAE is 0.05 g/cm3.

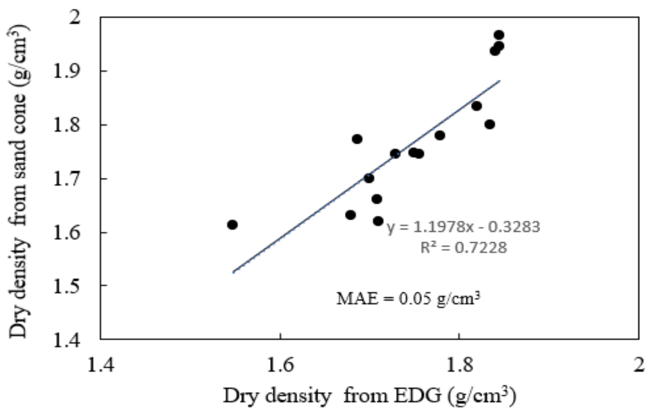

Fig. 14 *The scattered data of dry density*

Fig. 15 shows the scattered data of compaction Rc from EDG and sand cone. Linear regression analysis shows the value of R^2 is 0.3635 indicatingthe difference between EDG and sand cone is quitelarge, and the mean absolute error analysis is 2.76.

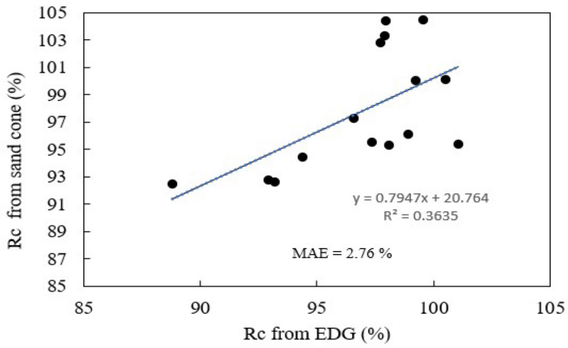

Fig. 15 *The scattered data of compaction*

6. Conclusion

EDG performance has been investigated using different soils from different quarries. Using sand cone method as a reference, it can be concluded that:

1. Concrete modified Proctor mold has been successfully utilized as a device for soil compaction for construction soil model for EDG in laboratory**.**
2. Compared to sand cone test, EDG shows a good performance for measuring soil moisture content, bulk density, and dry density with the value of determination coefficient R^2 are 0.7465 for moisture content measurement, 0,6105 for bulk density, and 0.7228 for dry density.
3. EDG shows a good performance indicated from relatively low mean absolute error MAE; 2.54% for moisture content, 0.07 g/cm³ for bulk density, and 0.05 g/cm³ for dry density.
4. The relatively low determination coefficient R^2 = 0.3635 for relative compaction measurement (Rc) is still acceptable due to uncertainty of soil condition. The value of MAE may be used by the engineer as a correction to relative compaction obtained from EDG measurement in the field.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Yusep Muslih Purwana, Bambang Setiawan;* ***data collection:*** *Mutiar Warman, Indah Suryaningtyas;* ***analysis and interpretation of results:*** *Yusep Muslih Purwana, Muchamad Rifai;* ***draft manuscript preparation:*** *Yusep Muslih Purwana, Bambang Setiwan, Indah Suryaningtyas. All authors reviewed the results and approved the final version of the manuscript.*

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