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EMPIRICAL ANALYSIS OF DENSITY VALUE BASED ON LABORATORY TEST AND GEOPHYSICAL LOG ON SEDIMENTARY ROCK

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ABSTRACT: The relationship model of counts per second (cps) and gr/cm^3 has been widely spread, but verification of whether the equation applies to all rocks have not been carried out much. The equation that is widely used in determining the correlation is the Warren equation. However, this equation needs to be verified to ensure whether it can be applied to all materials. This research aims to verify whether the Warren equation can also be applied to clastic sedimentary rocks which have low mechanical properties. This research also seeks to explore the relationship between cps and gr/cm^3 values in clastic sedimentary rocks. The variables in this research include density values resulting from laboratory testing and the measurement result of geophysical logging inside boreholes. The density variable consists of wet density and dry density, while the geophysical log variable consists of long-spaced density (LSD) and short-spaced density (SSD). The analysis was carried out by using regression with heteroscedasticity-consistent standard errors. The result shows that the Warren equation could not be applied to the sedimentary case. Besides, the conversion models of cps to gr/cm^3 for clastic sedimentary rocks that were built had a low predictive ability. Therefore, the determination of rock density is still recommended using laboratory tests of rock samples.

Keywords: Density, Count per second, gr/cm^3, Material properties

1. INTRODUCTION

In general, rock density is the ratio between the mass and the total volume of rock. There are five measurements of density, namely true density, apparent density, particle density, bulk density, and in-place density. True density is a division of the mass by the volume filled by free pores present in a solid. Precise determination of true density requires complete filling of the pore structure by a fluid that does not interact with the solid. Apparent density is determined by immersing the sample weight of a solid in a liquid, followed by measuring the accuracy of the liquid being transferred (pycnometer method). Bulk density is the mass of a collection of solid particles in a container divided by the volume of the container. The density value depends on true density, particle size, size distribution, particle shape, surface water content, and degree of compactness. In-place density should be determined on a saturated sample to adjust for the balance of water content that presents under in-situ conditions. In a simple manner, a rock has two components, a solid component and a pore component. The values of solid and pore components vary in each rock; therefore, the density of rock is different from the density of the other rock.

Rock density is used in slope geometry design by finding the unit weight of each slope rock (lithology) to design safe slope; in constructing road by finding the material density to design a road that can be passed by certain loads; and in selecting heavy equipment to carry out material excavation. Density correlates with depth, where the increase in depth leads to an increase in density due to the pressure of formation that causes a decrease in the void in rock mass [1].

Geophysical good logging is a method of recording subsurface data inside a borehole by detecting radioactive signals in each rock. The method measures and records the physical or lithological properties of formation at each depth. The continuously recorded data appear as a wireline log, which is used for investigating the response to variation of rock physical properties in a borehole. Radioactive is the act of decomposing atomic nuclei spontaneously and emitting alpha particles, beta particles, or gamma radiation. The emitted ray is referred to as a radioactive ray, while the substance emitting a radioactive ray is referred to as a radioactive substance.

Based on laboratory tests, bulk density has a strong negative relationship with neutron log value in coal [2]. When the bulk density (gr/cm^3) decreases, the neutron value will increase. A density log can be used to predict the mechanical properties of rock, which include uniaxial compressive strength (UCS), friction angle, and cohesion [3]. This study has not considered whether the density log also has a strong correlation with physical properties, and the limitations of the material used in the analysis need to be further defined. The deeper the rock, the more impact on increasing pressure [4,5]. Shear modulus, elastic modulus, and Poisson's ratio are also associated with depth as well as effective stress. This is closely related to density [6,7]. There is one interesting phenomenon in research on the relative density of rocks, where the researchers [8] conveyed the result of the study that the relative density of rocks (gr/cm^3) has a positive relationship with the relative density of logging interpretation result (gr/cm^3) with a degree of 0.7617. Every increase in relative density based on lab tests is always followed by an increase in relative density based on logging. Other studies have conveyed that log-based density and lab-based density have a negative relationship, where every increase in lab density value (gr/cm^3) will be followed by a decrease in log density (cps – count per second).

A tool that uses a radioactive ray source to measure the density of rock is a density log. It provides data on rock density along the borehole, which can distinguish the lithological type of rock. Porosity and the type of content therein, as well as rock compactness, have an impact on the values of rock density. This is because porosity is influenced by rock compactness. The different levels of density and porosity are owned by coal and other overburden, resulting in log data that clearly looks different.

The working principle of a density log, according to [9], is that a radioactive source from a measuring device emits gamma rays passing through rock formation at a specific energy level, where the rocks are formed from mineral grains composed of atoms consisting of protons and electrons. Gamma-ray particles strike the electrons in rocks, resulting in a collision that causes the gamma-ray energy to drop. The rock density affects the intensity of the reflected gamma ray, and then the detector at a specified distance from the source detects the energy that is released following the collision [10].

When the grains or minerals per volume are dense, which is indicated by a lot of electrons in the rock, the returned energy will be weak. Factors that influence the amount of energy received by the detector are:

1. Density of rock matrix
2. Rock porosity
3. Density of rock pores
4. Borehole diameter
5. Mud cake
6. Source-detector spaces: long-spaced density (LSD) or short-spaced density (SSD)

The distance between the radioactive source and the detector will affect the volume of rock investigated by the density log, so when the rock does not require high resolution, it can be used long-spaced density (LSD) [11]. There are two types of log density based on the source-detector space (Fig.1), which are long-spaced density (LSD) and short-spaced density (SSD). The applications for LSD log and SSD log are as follows:

1. When evaluating the subsurface, the LSD log may be used due to the small influence on the borehole wall, so the resulting density value is relatively close to the actual value. The source distance is ± 16 inches.
2. When measuring the thickness of the subsurface, an SSD log may be used due to its vertical resolution, which is higher than that of an LSD Log. The source distance is ± 7 inches.

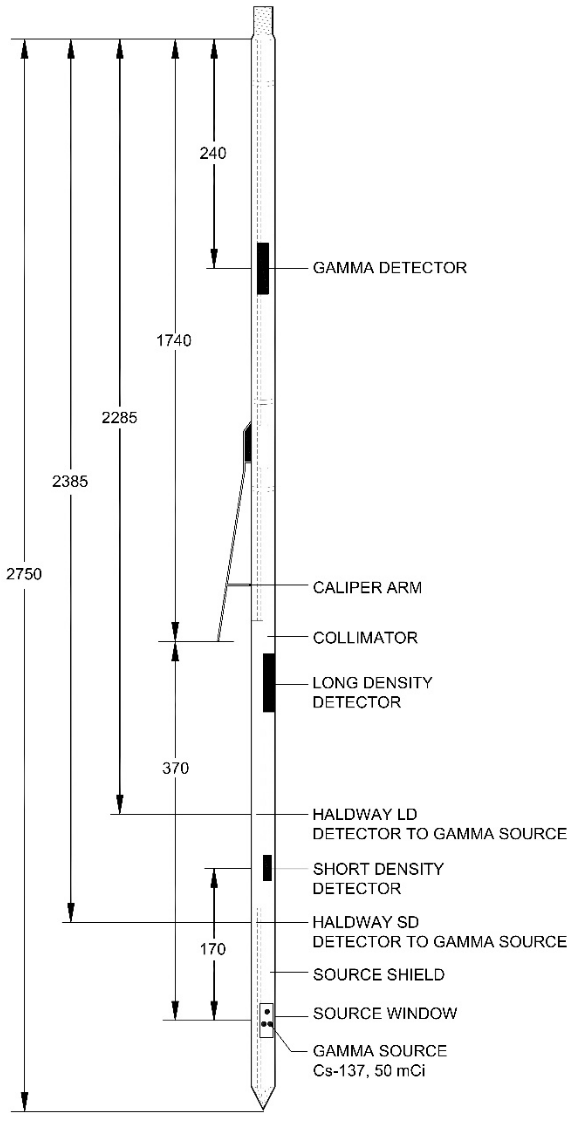

Fig.1 Long-spaced density (LSD) and short-spaced density (SSD) detectors [12]

In identifying evaporites, detecting gas zones, determining hydrocarbon density, and also monitoring shaly sand reservoirs and rock formations, geologists need density logs [13]. Eq. (1) is used to calculate porosity:

$$\Phi_{den} = \frac{\rho_{ma}-\rho_b}{\rho_{ma}-\rho_f} \quad (1)$$

where:
Φ_{den} = density value of porosity
ρ_{ma} = density of matrix or constant
ρ_b = density in a formation
ρ_f = density of the fluid (1.1 for salty mud; 1.0 for fresh mud)

In this research, the unit of log density is counts per second (cps). The cps is the number of atoms detected in a material that decays per second. The unit can be calibrated from cps to gr/cm^3 by using the model of cps and gr/cm^3, known as the Warren equation in Fig.2. Cps has an inversely proportional relationship with gr/cm^3, where a high value in gr/cm^3 unit leads to a low value in cps and vice versa. The relationship model is y = -2370.9x + 6945.4, where y is cps and x is gr/cm^3. To determine the gr/cm^3 value based on cps, the equation is modified into gr/cm^3 as new y (y') and cps as new x (x') (Eq. (2)):

$$y' = \frac{6{,}945.4-x'}{2{,}370.9} \quad (2)$$

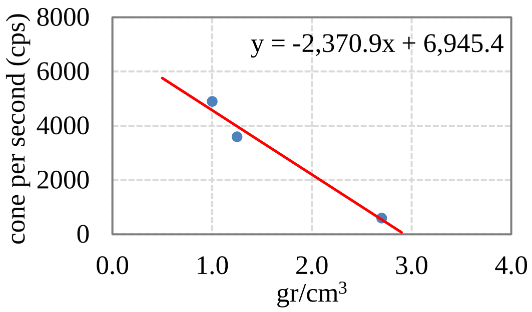

Fig.2 Warren equation showing an inversely proportional relationship between cps and gr/cm^3

2. RESEARCH SIGNIFICANCE

Determining the density is based on laboratory tests on rock samples. Obtaining samples of rocks distant from the earth's surface could be expensive and challenging, and the geophysical method is expected to be able to provide an overview of the rock density. The geophysical method is relatively quick and accurate with a lower cost than that of the core drilling method. This research may shed new light on optimizing geophysical logging, whose utilization has not yet been optimized. This research may also help in estimating rock density for various purposes.

3. MATERIAL AND METHOD

A density test was carried out on samples of sedimentary rocks from drilling activity by following ASTM 792-20. The geotechnical drilling activity to sampling is referred to as ASTM D2113-99. Description of sedimentary rocks used ASTM D5434-97 and ASTM D2488-00. The lithology of the research area is composed of sandstones which consist of fine to sandy quartz minerals [14] with a rupture angle of about 53° [15]. Claystone is composed of sand-sized quartz minerals with a few clay minerals in the form of kaolinite and illite [16]. Both of these rocks will experience deterioration when exposed, which degrades the physical and mechanical properties of the rock [17].

Geophysical logging was carried out in several boreholes at various depths. The locations were in a formation with the same geological characteristics. The logging was carried out at a speed of 5 m/min after boreholes had been cleaned from mud from drilling activity. The logging speed of 5 m/min is the optimum speed to produce stable data quality on the sedimentary rock [18]. Rock density was measured using GDDC (Gamma Dual Density and Caliper) type probe at both short-spaced density (SSD) and long-spaced density (LSD).

This research compares the density values from laboratory testing with the density values from geophysical logging inside boreholes. The unit of density based on laboratory testing is in grams per cubic centimeter (gr/cm^3), while the unit of density based on geophysical logging is in counts per second (cps). Warren equation in Eq. (2) was verified by converting the unit of density from geophysical logging using the equation and then comparing it with the density from laboratory testing. The relationship of density values based on geophysical logging before conversion and based on laboratory testing was also observed to determine the suitable conversion of cps to gr/cm^3 in sedimentary rock by using the regression analysis method. Referring to the Warren equation, the relationship was assumed to have a linear pattern.

The equation of linear regression for determining the relationship of density based on laboratory testing and density based on geophysical logging is (Eq. (3)):

$$Y = b_0 + b_1 X \quad (3)$$

where Y is density obtained from laboratory testing, b_0 is the regression constant, b_1 is the regression coefficient, and X is density obtained from geophysical logging. For simple regression (only one X), the model proposed is considered to be significant, or in other words, the relationship between X and Y can be determined by the model proposed when the p-value resulted from t-test statistics of regression coefficient is smaller than the specified significance level, which is 5%.

The results of regression analysis can be erroneous when there is a violation in the assumption of regression analysis. One of the assumptions that need to be met is homoscedasticity, which means that there are equal variances in the conditional distribution of Y. In pre-analysis, the violation of it was found, called heteroscedasticity. This influences the validity of statistical inference in regression through its effects on the estimates of standard errors of regression coefficient [19]. One of the alternatives that Darlington and Hayes [19] considered to deal with this situation is heteroscedasticity-consistent standard errors.

To know how well density based on the geophysical log (X) in the sample model predicts density based on laboratory testing (Y) in the population, shrunken R (R_S) is used. R_S close to 1 means higher predictive ability [20].

4. RESULT AND DISCUSSION

Warren equation (Eq. (2)) for converting cps to gr/cm^3 has been widely spread and believed to be true. This model equation has not been completely explained, how it is built, what the limitations are, and whether the equation can be implemented for all variations of lithology. The value of gr/cm^3 unit has a high sensitivity to its applications, such as in engineering, design, geotechnical, and other disciplines. So far, not many researchers have conducted empirical studies on how the equation is and whether it is valid for sedimentary rocks.

A density test in the laboratory was carried out by measuring the wet and dry density in a unit of gr/cm^3. Meanwhile, geophysical measurement was carried out using short-spaced and long-spaced detectors, which yielded density data in the unit of cps. There were 52 rock samples used for analysis. To verify the Warren equation (Eq. (2)), the density data obtained from the geophysical log were converted using the equation and then compared with the density data obtained from laboratory testing. Visualization of the results is in Fig.3. The results show that the error of short-spaced density (SSD) conversion using the Warren equation is much worse than the error of long-spaced density (LSD) conversion. In LSD conversion, the error ranges from 1.09% to 109.89% with an average of 28.96% for wet density, while for dry density, the error ranges from 0.15% to 112.09% with an average of 26.79%. In SSD conversion, the error ranges from 230.70% to 437.64%, with an average of 295.28% for wet density; while for dry density, the error ranges from 251.10% to 585.66%, with an average of 337.23%.

Based on the verification result, the Warren equation is definitely not for this research data. Therefore, a new conversion model of cps to gr/cm^3 was built using regression analysis. Since in pre-analysis, heteroscedasticity was found, the analysis used the regression method with heteroscedasticity-consistent standard errors. The results are in Table 1.

Table 1 Regression analysis result

	Estimation	Std. Error	t	p-value	R_S
LSD vs Wet Density					
Constant	2.147	0.065	32.840	0.000	-0.384
LSD	-3.76×10^{-5}	2.11×10^{-5}	-1.778	0.081	
LSD vs Dry Density					
Constant	1.864	0.077	24.247	0.000	-0.424
LSD	-5.37×10^{-5}	2.50×10^{-5}	-2.147	0.037	
SSD vs Wet Density					
Constant	2.645	0.257	10.285	0	-0.374
SSD	-3.88×10^{-5}	1.65×10^{-5}	-2.357	0.022	
SSD vs Dry Density					
Constant	2.528	0.323	7.821	0.000	-0.38814
SSD	-5.24×10^{-5}	2.07×10^{-5}	-2.531	0.015	

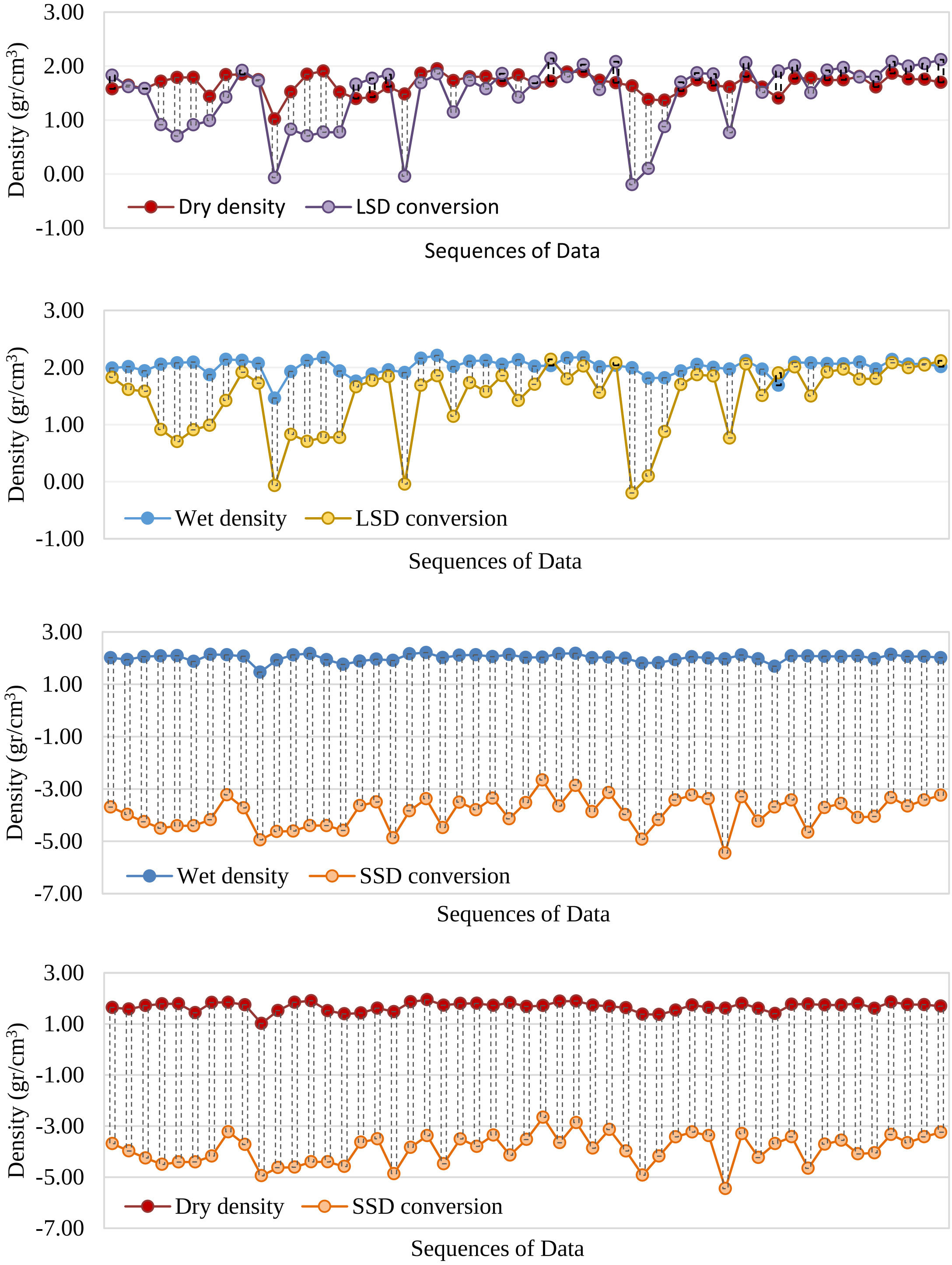

Fig.3 Comparison of wet and dry densities with conversions of long-spaced density (LSD) and short-spaced density (SSD) using the Warren equation

Most of the LSD values (80%) ranged from 2000 to 3500 cps, 15% were in the range of 4200 to 5200 cps, and 5% were in the range of 6750 to 7,00 cps. Wet density from laboratory tests was in the range of 17 to 2.2 gr/cm^3 and only about 10% was below 1.7 gr/cm^3. The relationship model of LSD and wet density is as follows:

$$\text{Wet density} = 2.147 - 3.76\times10^{-5}\ \text{LSD} \quad (4)$$

Based on the result in Table 1, the model is not significant, known from the p-value of 0.081, which is greater than the significance level of 0.05. The R_S of -0.384 shows that the predictive ability is low. Meanwhile, dry density from laboratory tests ranged from 1.5 to 2.0 gr/cm^3 and <10% were below 1.5 gr/cm^3. The relationship model of LSD and dry density is as follows:

Dry density = 1.864 - 3.88×10^{-5} LSD (5)

The p-value of 0.037 (Table 1) is smaller than the significance level of 0.05; therefore, the model is significant. The R_S of -0.424 also shows that the predictive ability is low. The plot of LSD and wet density and dry density is presented in Fig.4 and Fig.5, respectively.

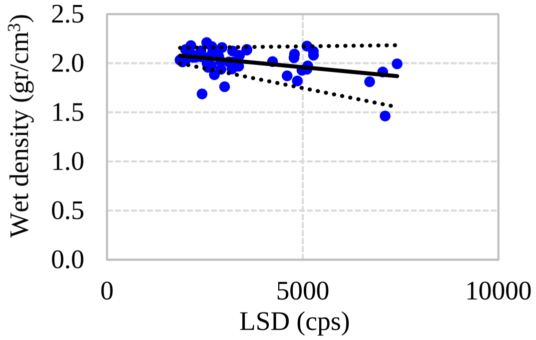

Fig.4 Plot of long-spaced density (LSD) and wet density

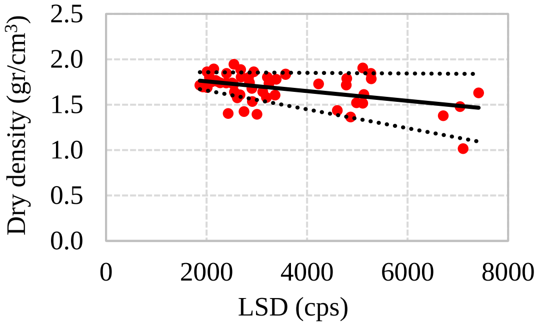

Fig.5 Plot of long-spaced density (LSD) and dry density

Most of the SSD values (80%) ranged from 14,500 to 18,000 cps and 10% were outside the range. The relationship model of SSD and wet density is as follows:

Wet density = 2645 - 3.88×10^{-5} SSD (6)

Based on the result in Table 1, the model is significant, known from the p-value of 0.022, which is smaller than the significance level of 0.05. The R_S of -0.374 shows that the predictive ability is low. For dry density, the relationship model with SSD is as follows:

Dry density = 2528 - 5.24×10^{-5} SSD (7)

The p-value of 0.015 (Table 1) is smaller than the significance level of 0.05; therefore, the model is significant. The R_S of -0.388 also shows that the predictive ability is low. The plot of SSD and wet density and dry density are presented in Fig.6 and Fig.7, respectively.

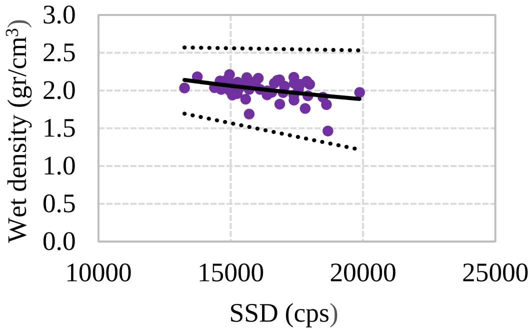

Fig.6 Plot of short-spaced density (SSD) and wet density

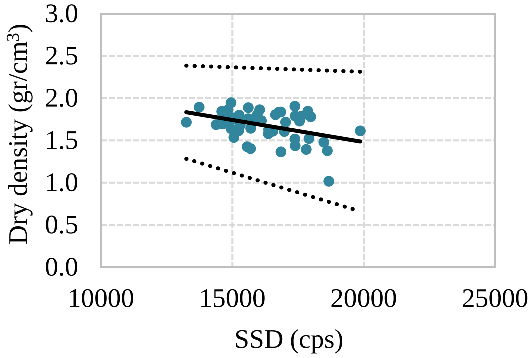

Fig.7 Plot of short-spaced density (SSD) and dry density

5. CONCLUSION

Warren equation cannot be applied to clastic sedimentary rock with low mechanical properties. The conversion result using the equation yields negative values, especially for short-spaced density (SSD) data. The model conversions of both short-spaced density (SSD) and long-spaced density (LSD) built from regression analysis also show a poor result. The predictive ability is low, based on the shrunken R (R_S). Hence, density values in a unit of cps obtained from both LSD and SSD logging cannot estimate well the actual density values in a unit of gr/cm^3 which are obtained from laboratory testing for both wet and dry density. Determination of rock density is still recommended using laboratory tests of rock samples instead of a conversion model. The conversion model needs to be redefined regarding the population and the variables. A larger sample size may also help to get a better result. In order to fulfill the local condition and to improve the accuracy of further analysis, it is required to modify the equation by adjusting the coefficients in the equation, so a more realistic and more suitable density model for the observed data will be obtained. As a result, it can minimize the errors produced in analyzing the type of rock.

Since each rock has its own characteristics, a conversion model of cps to gr/cm^3 must be built for each characteristic of the rock. This shows that there is an open space for the researcher to determine the conversion model with the aim of utilizing geophysical data, which are abundant for various purposes.

6. ACKNOWLEDGMENTS

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