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EFFECTS OF GEOMECHANICAL PROPERTIES ON MATERIALS ADHESIVITY

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ABSTRACT: Material properties is one of the most significant variables in terms of efficiency. The sediment layer in a coal pit mine has a possibility of sticking to the equipment bucket and reducing its productivity, especially in the disposal area. Consequently, stickiness has a close definition of adhesivity level; thus it may be associated with geomechanical properties. Various soil classification in the disposal area was investigated to identify the relationship between adhesivity and geomechanical properties such as water content, density, cohesion, and internal friction angles. Multivariate regression analysis and statistical test (F-test and t-test) were used to investigate geomechanical properties related to adhesivity on each disposal area. Primary data was taken from a standard and modified laboratory testing. The results showed that disposal materials were high-plasticity materials with different grain-sizes. The dominant grain size on disposal 1, 2, and 3 were clay, sand, and clay, respectively. Based on regression analysis, the adhesivity on each disposal was increased along with the water content until its optimum value. Using a statistical test with a significance level of 95% (P-value 0.04), water content, cohesion and internal friction angle affected the adhesivity level on disposal 1 by 99% (adjusted R^2 0.99). Adhesivity level in disposal 2 was only affected with density by 63% (adjusted R^2 0.63). Meanwhile, in disposal 3, the significance level of 33% (P-value 0.50) was used to define that water content, cohesion, and internal friction angle as parameters affecting adhesivity level by 33% (adjusted R^2 0.33).

Keywords: Adhesivity, Geomechanical properties, Linear regression, Multi-variate analysis.

1. INTRODUCTION

Productivity in mining operations is consequently affected by certain parameters such as equipment and material properties. It is recognized that mining equipment has significant roles in improving productivity. Therefore, material properties should be addressed carefully. In layered deposits with predominantly sediment rock formations such as coal mining, material properties become an important factor in productivity considerations. A sediment layer has a possibility to stick onto an equipment bucket and reduce its productivity, especially in the disposal area.

Stickiness in the material referring to adhesive force [1]. Adhesiveness is related to the tensile force between the soil material and the bucket of the equipment, also the tensile force between the material itself. This condition might cause the sticky material to become thicker.

Multiple researchers studied the geomechanical properties in correlation with adhesivity. Hendrick and Bailey [2] stated that soil adhesivity characteristics affect the stickiness level and soil consistency. Harsono [3] investigated the adhesivity of soil and various materials with soil water content. Thus, adhesivity could be correlated with the geomechanical properties. However, those studies [2, 3] only focused on clay-typed soil. Other studies related to this subject mostly investigated shear strength parameters such as cohesion (c) and internal friction angle (ϕ) on soils [4, 5, 6]. Moreover, geochemical studies focused on adhesion were infrequent. The correlation of adhesion to multiple parameters of geochemical properties (i.e., physical and mechanical properties) remains uncertain.

Therefore, in this study, multiple types of soil classification in the disposal area were investigated. This study aimed to quantify adhesivity and the relation with geomechanical properties such as density, water content, cohesion, and internal friction angle. The selected geomechanical properties were selected due to the familiar parameters of soil.

2. RESEARCH SIGNIFICANCE

The references pertaining to the soil classification from disposal area in the coal mining industry are not widely available and still limited [2, 3]. These soil classifications have critical aspects in mining productivity deliberation due to its geomechanical properties, especially related to the adhesivity level. This study will emphasize the determination of adhesivity value and the relation with geomechanical properties (e.g., density, water content, cohesion, and internal friction angle). The most affected parameters to the adhesivity level could be indicated by this correlation. In the practical case, the correlation would assist the next strategies to increase mechanical equipment productivities in mining operation.

3. MATERIALS AND METHODS

The research area is located in the disposal area of a coal mining site located in Muara Enim, Indonesia. The soil samples with varied grain size composition structures were collected at depth 13 – 55 m from the surface from three areas, namely disposal 1, disposal 2, and disposal 3 (Fig. 1). A group of samples was taken for testing physical properties, grain distribution (sieve analysis), hydrometer, and uniaxial compressive strength in each disposal area. Simultaneously, more samples were also collected from each disposal area for consistency testing (Atterberg's limit), direct shear test, and adhesiveness.

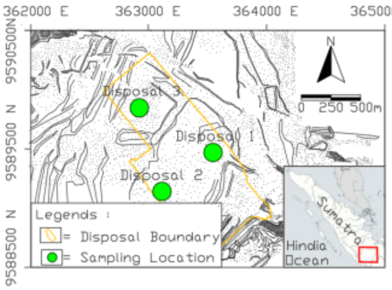

Fig. 1. Research area and sampling location

3.1 Sample Preparation

The number of samples considered the adequacy of the minimum sample requirements for each laboratory test parameter. All samples were undisturbed and placed in the thin wall tube (50 cm in length; 3 inches of diameter), which the structures, water contents, and chemical composition did not change. The samples were then transported to Soil Mechanics Lab of Universitas Pembangunan Nasional "Veteran" Yogyakarta.

3.2 Testing Method

In general, the laboratory testing method in this study was divided into (i) physical properties, (ii) mechanical properties, and (iii) adhesivity tests. The previous secondary data measured from 2011 – 2016 in the same disposal area were also evaluated for compilation.

The physical properties consisted of density, specific gravity, moisture content, void ratio, porosity, and degree of saturation. The density and specific gravity were measured by a pycnometer (50 mL) with the standard of American Society for Testing and Material (ASTM) D854-58 [7]Moisture content, void ratio, porosity, and degree of saturation were measured with the standard of ASTM D2216-71 [8]. Physical properties tests obtaining parameters of unit weight and density were also conducted with the standard of ASTM D7263-09 [9]. In addition, the consistency test (Atterberg limit) was also conducted to determine the disposal type based on the levels of plasticity index (PI). The levels were classified into low (PI < 7%), medium (PI 7 – 17%), and high plastic (PI > 17%) [10]. The standard method used for Atterberg's limit test in this study was ASTM D4318-17 [11] by measuring the ratio of the water weight in the pore space with the weight of dry soil at the liquid limit (LL) and plastic limit (PL) conditions. Particle-size was analyzed by ASTM D422-63 [12]. Meanwhile, the mechanical properties consisted of cohesion and internal friction angle. These properties were measured by the direct shear test with the standard of ASTM D3080-9 [13].

On the other hand, the adhesive test in the laboratory was conducted with a direct shear testing illustrated in Fig. 2. The approach of the test was similar to the concept of the Mohr-Coulomb. However, in another case with the original direct shear obtaining a cohesion value, the shear device's friction plane in this study was modified with a steel plate to obtain the adhesion value from the friction force between soil and surface of the steel plate. Fig. 3a describes the interpretation of the difference in yield parameters in the original direct shear test, while Fig. 3b illustrates the modified test in this study.

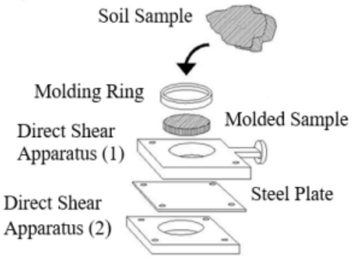

Fig 2. Illustration of adhesivity test

After unpacking samples from the thin wall tube and plastic bags, the soil samples were molded in the ring (1.7 cm of height; 3 cm of diameter). The soil height was half of the ring. Then, the molded samples were placed in the modified direct shear test apparatus, where the dial gauge deformation and normal force were applied. The testing was conducted by measuring the shear force on the proving ring from each deformation. The test was completed when the shear force decreased. The samples were measured three times with different normal forces.

In addition, secondary data of soil physical and mechanical properties in vicinity disposal of research area were also used for compilation. These data were collected in 2011 – 2017 and measured in Soil Mechanics Laboratory of PT Bukit Asam, Tbk.

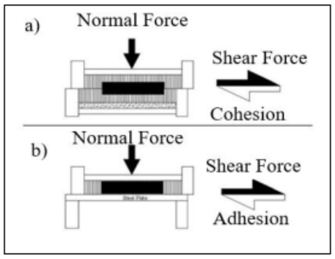

Fig. 3 Cohesion and adhesion parameters in direct shear tests

3.3 Data Analysis

The primary and secondary data were evaluated to ensure data characteristics in this study. The secondary data of geomechanical parameters in this study was used as a validation of the primary data. The validation methods using statistical parameters such as central tendency value (mean, median, and mode) and standard deviation. Geomechanical parameters (physical and mechanical properties) obtained from laboratory testing were analyzed using statistical methods of linear regression. The principle of least square was used in this study to minimize variance and errors.

Data analysis softwares such as R, MatLab, and Ms. Excel were used as data processing tools in this study. The regression equation was evaluated using "F" and "t" statistical test. The t-statistical test was used to evaluate an influencing parameter partially. Meanwhile, the F-statistical test was used to evaluate an influencing parameter simultaneously. An error tolerance level of 10% (significance level of 90%) and P-value < 0.1 were the best regression equation criteria. The R-square value is also used to provide information about the independent variable's contribution towards the dependent variable.

Multiple Linear Regression (MLR), also known as multivariate regression analysis, is the most often used regression model to analyze a dependent variable on the basis of change in more than one independent variable [14]. Based on the degree of freedom and the amount of data analyzed in the regression analysis, a composition of multivariate regression has a maximum of three parameters. In this study, multivariate analysis was investigated through various parameters until the maximum number of parameters. Thus, the multivariate linear regression analysis on each disposal was tested on 14 equations with details as follows: four equations on three parameters, six equations for two parameters, and four equations for one parameter. The adjusted R^2 was used because the number of independent variables is more than one (multivariate regression). The higher of adjusted R^2 value indicates that the added of independent variable would affect the dependent variable.

4. RESULTS`

4.1 Physical Properties

The physical properties data showed that mean values of water content, void ratio, porosity, and degree of saturation in the study area were 21.97%, 0.68, 40.35%, and 86.4%, respectively. The standard deviation for those properties were 0.22 – 11.79%. Table 1 shows the detailed statistical resume of physical properties from 77 data including moisture content, pore value, porosity, and degree of saturation.

The natural density had the mean of 19.25 kN/m^3 with the standard deviation of 1,47 kN/m^3. Meanwhile, mean and standard deviation of the dry density were 15.67 kN/m^3 and 2.02 kN/m^3, respectively. The detailed density data of disposal material from 154 data are presented in Table 2.

Table 1. Water content, water value, pore value, porosity, and degree of saturation

Statistical Parameters	Physical Properties Parameters			
	Water content (%)	Void ratio	Porosity (%)	Degree of saturation (%)
Mean	21.97	0.68	40.35	86.4
Median	20.45	0.63	38.83	87.62
Standard Deviation	7.67	0.22	9.92	11.79
Range	39.92	1.05	76.74	75.75
Minimum	8.06	0.30	22.79	49.63
Maximum	47.98	1.34	57.34	98.81

The unit weight tests showed around 1.32 – 1.62 gr/cm^3 for unsaturated. The results for saturated unit weight (1.57 – 2.03 gr/cm^3) were about 25% higher than that of unsaturated. The measurement also showed a high natural water content of 19.04 – 35.8% (Table 3).

Table 2. Density parameters

Statistical Parameters	Natural Density (kg/m^3)	Dry density (kg/m^3)
Mean	1962.96	1597.90
Median	1960.92	1594.84
Modus	2039.44	1613.19
Standard Deviation	149.90	205.98
Data range	714.82	1035.01
Maximum	1650.92	1139.02
Minimum	2365.75	2174.04

The consistency test (Atterberg's limits) results showed that the plasticity index values in disposal 1, 2, and 3 were 26.64%, 19.73%, and 18.00%, respectively (Table 4). Although all samples had same classification as high plastic, the sample in disposal 3 was in the highest PI while the sample in disposal 2 was the lowest. This test's PI values were consistent compared to the previous tests in the vicinity disposal area, which was dominated by high plastic materials (>17% of PI) with a percentage of 66.23%. The materials with medium plastic were identified with 33.77%, while low plastic materials were unidentified.

Table 3. Saturated and unsaturated unit weight

Sample Code	Unsaturated unit weight	Saturated unit weight
	kN/m^3	kN/m^3
Disposal 1	12.94	15.78
	13.03	16.27
	12.94	16.56
	13.62	18.33
	12.94	15.39
Disposal 2	14.11	16.95
	14.80	18.13
	15.39	19.21
	14.90	19.21
	14.60	19.89
Disposal 3	13.82	17.84
	14.70	18.13
	15.88	19.11
	15.29	17.74
	14.70	18.13

Table 5 shows that the grain size of soil in disposal 1 was dominated by clay with a percentage of 47.28%, followed by silt with 47.22% and submissive aggregate grain size of sand (5.50%). On the contrary, in the disposal 2, sand was the major grain size with percentage of 47%, while the grain sizes of clay and silt were 21.86% and 31.14%, respectively. Meanwhile, in the disposal 3, the percentages grain size distribution of clay, silt, and sand were 48.00%, 47,00%, and 5.00%, respectively. This distribution in disposal 1 had a similar percentage compared to that of in the disposal 1.

Table 4. Results of consistency test

Sample Code	Atterberg Limit (%)			Plasticity Index
	PL	LL	PI	
Disposal 1	15.82	42.46	26.64	High Plastic
Disposal 2	14.77	34.5	19.73	High Plastic
Disposal 3	28	56	28	High Plastic

Table 5. Grain size distribution of disposal material

Sample Code	Grain Size Distribution (%)			
	Clay	Silt	Sand	Gravel
Disposal 1	47.28	47.22	5.50	0
Disposal 2	21.86	31.14	47.00	0
Disposal 3	48.00	47.00	5.00	0

4.2 Mechanical Properties

The results of direct shear tests showed that the disposal samples' cohesion values were in the range between 0.07 and 0.62 kg/cm^2, while the friction angles were in the range between 16.17^o and 27.02^o (Table 6). These primary data were consistent compared to the statistical resume of the disposal materials based on the previous laboratory tests (Table 7). The mean, standard deviation, minimum, and maximum values of residual cohesion from 88 data were 0.22, 0.16, 0.21, and 1.07 kPa, respectively. Meanwhile, mean, standard error, standard deviation, minimum, and maximum values of residual friction angle were 15.77, 0.60, 5.62, 4.33, and 26.94 kPa, respectively.

4.3 Adhesivity Values

The results of adhesiveness tests (Table 8) showed that materials in disposal 1 were the most adhesive with an average value of 0.21 kg/cm^2. These adhesive values in disposal 1 were about two times higher than those of materials in disposal 2 (0.10 kg/cm^2 of average). Meanwhile, materials in disposal 3 had the average adhesive values of 0.07 kg/cm^2, less than those of disposal 2. The water contents in Table 8, which were directly measured after the adhesivity test, showed the values between 19.08 – 34.71% for materials in disposal 1, 20.00 –

35.80% for materials in disposal 2 18.22 – 27.7% for materials in disposal 3. Friction angles of all disposal materials were 16.70° – 27.02°.

Table 6. Primary data of mechanical properties

Sample code	Cohesion (kPa)	Inner friction angle (°)
Disposal 1	36.28	21.85
	42.17	21.85
	36.28	21.85
	18.63	26.61
	45.11	21.85
Disposal 2	35.30	26.61
	32.36	21.85
	22.56	21.85
	27.46	16.70
	14.71	21.85
Disposal 3	60.80	27.02
	10.79	18.31
	6.86	18.77
	34.32	18.57
	37.27	18.59

Table 7. Previous data of mechanical properties

Statistical Parameters	Direct Shear Parameters	
	Residual Cohesion	Residual Internal Friction Angle
	Cr (kPa)	ϕr (°)
Mean	21.57	15.77
Median	18.63	15.15
Modus	28.44	11.20
Standard Deviation	15.69	5.62
Data Range	101.99	22.61
Minimum	20.59	4.33
Maximum	104.93	26.94

4.4 Multivariate Effects of Geomechanical Properties on Adhesion

The independent parameters that used in the analysis written with a notation of x_1, x_2, x_3, and x_4, which explained geomechanical properties such as water content, cohesion, density, and internal friction angle, respectively. The result shown in Table 9 was the best-fit equations from each number of parameters used in the multivariate regression analysis. Based on multivariate regression analysis on disposal 1, water content and internal friction angle were shown to be the most affecting adhesivity parameter (P-value 0.04). A partial statistical test (t-test) was conducted on this point onward. Water content, cohesion, and internal friction angle parameters were significant parameters to adhesivity with P-value of 0.02, 0.1, and 0.05, respectively. The intercept value also showed as a significant parameter to adhesivity with a P-value of 0.3).

Table 8**.** Disposal adhesiveness test results

Sample code	Adhesion (kPa)	Water content (%)	Internal friction angle (°)
Disposal 1	11.77	21.87	21.85
	28.44	25.25	21.85
	32.36	27.6	21.85
	22.56	34.71	26.61
	6.86	19.08	21.85
Disposal 2	2.94	20.00	26.61
	13.73	22.65	21.85
	12.75	24.77	21.85
	11.77	29.41	16.70
	8.83	35.80	21.85
Disposal 3	6.86	18.22	27.02
	4.90	23.68	18.31
	12.75	24.89	18.77
	3.92	25.12	18.57
	4.90	27.7	18.59

In disposal 2, density has shown as the most significant parameter that affecting adhesivity based on multivariate regression analysis (P-value 0.067). The t-test was conducted to investigate the significance of density and intercept, resulting in P-value of 0.067 and 0.082, respectively. In disposal 3, no parameter passed the statistical tests (F-test and t-test) with a significance level of 90%. The best equation was shown on a significance level of 50%, including density and internal friction angle parameters (P-value of 0.502). Based on statistical t-test, water content, cohesion, internal friction angle, and intercept showed a P-value of 0.4, 0.27, 0.32, and 0.38, respectively.

5. DISCUSSION

The disposal characterization in the research area is notably related to the aggregate volume of the soil porosity (Table 1), density (Table 2), and unit weight (Table 3). The high percentage of pores (40.35%) indicates that the soil was looser because of the great amount of space between the soil grains. The porosity percentage on the soil has a negative effect on the value of the original soil density (Fig. 4). The higher porosity in the soil aggregate, the decreased value of the weight of the contents. This relationship between porosity and density is illustrated through a non-linear regression with a high coefficient of determination (0.90).

On the contrary, a positive correlation between porosity and water content in the study site's material disposal was identified in the form of linear regression by 0.90 (Fig. 5). This relation proved that the greater the value of the water in the soil represents the percentage of pores or space between the grains in a soil aggregate. Therefore, the greater space between grains also defines the greater space provided by soil aggregates in storing water under saturated conditions.

Table 9. Multivariate regression equation

Material	Equation	Description
Disposal 1	$\boldsymbol{y = 19.07 + 3.70x_1 + 0.67x_2 - 5.17x_4}$....(1)	Adjusted R^2 = 0.996 P-value = 0.04034
	$\boldsymbol{y = 229.12 + 3.98x_1 + 0.98x_2 - 31.78x_3}$.... (2)	Adjusted R^2 = 0.1476 P-value = 0.946
	$\boldsymbol{y = -352.55 + 3.08x_1 + 44.95x_3 - 12.93x_4}$.... (3)	Adjusted R^2 = 0.9354 P-value = 0.1613
Disposal 2	$\boldsymbol{y = -107.67 + 7.97x_3}$ ..... (4)	Adjusted R^2 = 0.6348 P-value = 0.06673
	$\boldsymbol{y = -74.69 + 6.29x_3 - 0.38x_4}$ ..... (5)	Adjusted R^2 = 0.5757 P-value = 0.2121
	$\boldsymbol{y = -114.33 + 0.052x_2 + 8.33x_3}$..... (6)	Adjusted R^2 = 0.4685 P-value = 0.2658
Disposal 3	$\boldsymbol{y = -86.84 + 1.76x_1 - 0.32x_2 + 3.01x_4}$ ..... (7)	Adjusted R^2 = 0.3327 P-value = 0.5052
	$\boldsymbol{y = -96.26 + 5.67x_3 + 0.92x_4}$ .... (8)	Adjusted R^2 = 0.3205 P-value = 0.3398
	$\boldsymbol{y = -78.26 - 0.12x_2 + 4.26x_3 + 1.24x_4}$.... (9)	Adjusted R^2 = 0.3006 P-value = 0.5165

Note: x_1: water content; x_2: cohesion; x_3: density; x_4: internal friction angle

Moreover, the water contents (Table 1) also considerably influenced the adhesivity of the samples (Table 5). The adhesivity values were proved to increase with the water content. Nevertheless, on one point, the adhesivity value would reach the peak value. After this point onward, the adhesivity value decreased by increasing the water content (Fig. 6). These results were consistent with the previous study [15]. Another study [16], also stated that maximum adhesive value could be reached when water contents are between plastic and liquid limit.

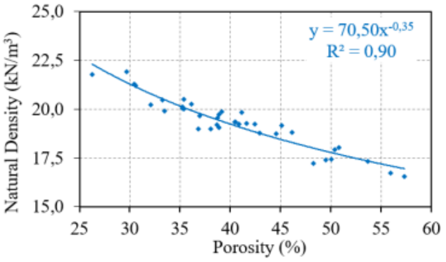

Fig. 4 Porosity effect on disposal natural density

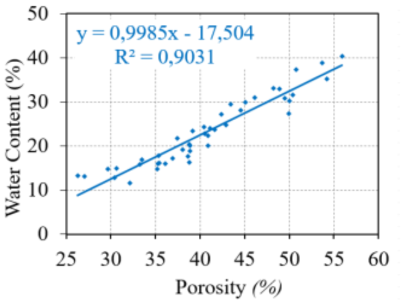

Fig. 5 Porosity effect on disposal water content

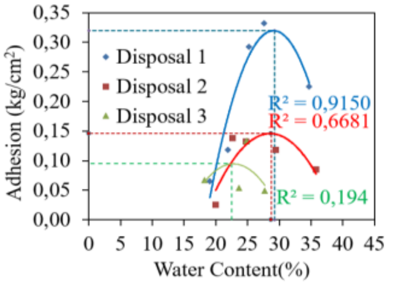

Fig. 6. Effect of water content on disposal adhesion

Based on Fig. 6, the peak phase of adhesion in disposal 1 was 0.33 kg/cm^2 with 29.21% of moisture content. This peak adhesion in disposal 1 was significantly higher by twice than that of adhesion value in disposal 2 (0.14 kg/cm^2), though the water content was slightly lower (28.73%). High adhesion corresponded to the clay material which was dominantly composed disposal 1. Besides, low adhesion was influenced by the sand materials in disposal 2. These results support the previous studies [15, 16], which stated that clay materials are more adhesive than sand materials. The lowest adhesion results (0.09 kg/cm^2) in disposal 3 were unexpected since clay and silt were the dominant materials, almost similar to disposal 1. This fact suggested that disposal 3 might be composed of a mixture of overburden from different parent materials with different cation exchange capacity [15, 16].

The correlative relationship between the percentage of grain size and the plasticity index is illustrated through linear regression (Fig. 7). The coefficient of determination on the graph points that the influences of the clay and sand grain sizes distribution to the plasticity index are 0.70 and 0.50, respectively. The sand grain sizes' relationship curve indicated that the greater percentage of sand content in the soil leads to the decreases of plasticity index in the soil. In contrast, the curve in the size of clay grains defines a positive relationship, where an increase in the percentage of the amount of clay content would cause an increase in the soil plasticity index.

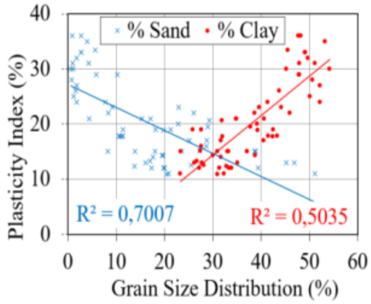

Fig. 7. Grain size effects on plasticity index

In disposal 1 (Table 9), the multivariate effect from water content (x_1), cohesion (x_2), and inner friction angle (x_4) provide the linearity effect for adhesivity value (y) in Eq. (1). R-squared value for this relation is 0.996, indicating that relation from two parametric effects 99.6% for adhesivity value.

The intercept giving information that without the effect of other parameters, the adhesivity value has a consistent value of 19.07 kPa. Every 1% of increased water content will increase the adhesivity value by 3.7 kPa. Every 1 kPa of increased cohesion would decrease 0.67 kPa the adhesivity value. Also, every 1° of increased internal friction angle would increase the adhesivity value by 5.17 kPa. Correlation from these parameters generates the adjusted R-squared value of 0.996 and percentage error of 4%. The correlation between each variable is shown in Fig. 8. The red box showed relation between adhesivity (x-axis) and water Content (y-axis). The green box showed relation about water content (x-axis) and adhesivity (y-axis).

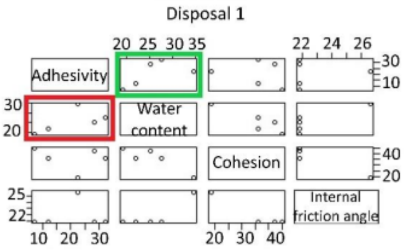

Fig 8. Graphic of water content, cohesion, and internal friction angle on adhesivity value relation

In disposal 2 (Table 9), the multivariate effect from density (x_3) provides the linearity effect for adhesivity value (y) in Eq. (4). The density and adhesivity values have a positive slope. This means that every 1 kg/m^3 of increased density value would increase 7.97 the adhesivity value (Fig. 9).

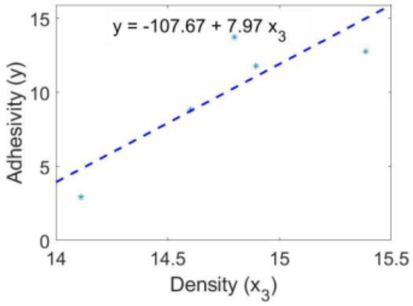

Fig. 9. Graphic of density effect for adhesivity value

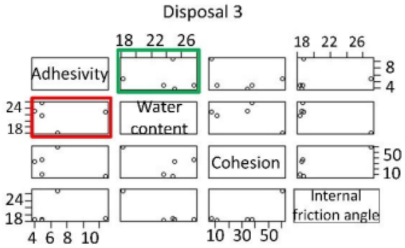

Fig. 10. Graphic of water content, cohesion, and internal friction angle for adhesivity value

In disposal 3 (Table 9), the multivariate effect from density and internal friction angle with 50% significance level suggests a linearity effect for adhesivity value in Eq. (7), which also agrees with the previous studies that used a similar parameter [17]. This relation describes that the R-squared value is 0.5052 and 50.52% from adhesivity value is affected by water content, cohesion, and internal friction angle. Every 1% increased water content would increase 1.768 kPa the adhesivity value. The correlation between each variable is shown in Fig.10. Every 1 kPa of increased cohesion would decrease 0.3255 kPa the adhesivity value. Every 1° of increased internal friction angle would increase 3.0111 kPa the adhesivity value.

6. CONCLUSION

Based on the relationship between adhesivity and geomechanical properties investigated, it can be concluded as follows:

a. Geomechanical properties, especially physical properties (i.e., density, plasticity, water level and grain size), affect individual adhesivity value.
b. The multivariate regression analysis indicates that each disposal had different parameters with a significant adhesivity level. The adhesivity level in disposal 1 is affected by water content, cohesion, and internal friction angle; in disposal 2 is density. Meanwhile, adhesivity in disposal 3 is affected by water content, cohesion, and internal friction angle.

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