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Compaction Effect on Open-Pit Coal Mine Disposal Material: An Experimental Study, South Kalimantan, Indonesia

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Abstract

Disposal slope stability is a significant matter in open-pit coal mines. Mechanical compaction of disposal materials made of sand-clay mixtures is essential for regulating slope stability and total disposal capacity. This study investigates the effect of mechanical compaction using a 20-ton vibratory compactor on the compaction characteristics and dry density of disposal material. Field investigation was conducted at disposal Block K and Block G of an open-pit coal mine in South Kalimantan, Indonesia, where the materials consist of sandstone-claystone mixtures derived from the Warukin Formation. A large sampling tube (13.3 cm diameter) was used to collect undisturbed samples at depths of up to 1.5 m along multiple disposal lanes that were mechanically compacted. For validation, the measured density values were then compared to California Bearing Ratio estimates derived from Dynamic Cone Penetrometer tests. Field test results with a 2 m lift dumping layer indicate that additional compaction using a 20-ton compactor applied over 40 passes significantly increased dry density value of the disposal material. At a depth of 0.3 m, dry density increased from 1.56 g/cm³ to 1.90 g/cm³ in Block K and from 1.23 g/cm³ to 1.69 g/cm³ in Block G.

Keywords: Mechanical compaction; Dry density; Open-pit coal; Disposal material; Warukin Formation; Disposal capacity

1. Introduction

Open-pit coal mining operations, which typically use strip mining or open-pit mining techniques, pose a significant challenge regarding the placement of overburden material in disposal areas due to their effect on operational and geotechnical aspects of a mine. To improve disposal capacity while preserving long-term stability, disposal design optimization is crucial (Das et al., 2023). Applying mechanical compaction with heavy machinery, like vibratory compactors, to raise the density of dumped materials is one way to improve disposal performance.

Characteristics of the disposal material, number of compaction passes, and soil layer thickness are all indicators of field compaction efficiency. This research examines the necessary compaction parameters to elevate the density of disposed material to levels comparable to the initial rock mass, focusing specifically on the impact of the total number of passes made by the compactor. Several considerations were derived from previous studies. Mechanical compaction of lateritic materials placed on haul roads has shown that 10 compactor passes are sufficient for fine-grained materials and 15 passes for coarse-grained materials at a lift thickness of 40 cm (Supandi, 2015). Compaction has been reported

as most efficacious at shallow depths, with the strongest influence observed at approximately 12.5 cm, whereas its impact markedly wanes with increasing depth (Powalka and Bulinski, 2014). Significant compaction effects generally occur within the upper 0-30 cm, whereas densification below this depth requires substantially higher loads and a larger number of passes. Beyond depths of approximately 45 cm, the influence of machine passes becomes negligible (Patel and Mani, 2011). For granular soils, dry density has been shown to increase linearly with the number of compactor passes, with at least 12 passes required to achieve 95% of the maximum dry density (MDD) for a 20 cm compacted layer (Niphadkar, 2016). Additionally, compaction-induced densification is more likely to occur in materials with high initial void ratios and sufficient pathways for air and water expulsion under applied loading (Ismail et al., 2020). The correlation between maximum dry density (MDD) and optimum moisture content (OMC) has been shown to be robust and consistent, serving as a fundamental basis for soil compaction quality control (Spagnoli and Shimobe, 2020; Rubinos et al., 2015). Resistivity measurements are also used as an alternative technique for estimating soil density (Melo et al., 2021). Undisturbed sampling combined with laboratory testing is used to rapidly determine natural density, dry density, and moisture content in coal mine disposal materials, and the results are then validated against California Bearing Ratio (CBR) values estimated from Dynamic Cone Penetrometer (DCP) testing (Sidiq et al., 2025).

The disposal material consists of overburden and interburden mixed, derived from sandstone and claystone of the Warukin Formation, which exhibit relatively soft mechanical properties (Supandi, 2020). The overburden and interburden materials were excavated predominantly by free digging methods, while blasting was used locally in relatively harder zones. Under existing disposal conditions, the dry density of the disposal material ranges from 1.09 g/cm³ to 1.56 g/cm³, all of which are below (MDD) value obtained from laboratory compaction testing.

The aim of this study was to determine the effect of mechanical compaction using a 20-ton compactor on the density of disposal materials at various depths within a coal mine disposal area in South Kalimantan, Indonesia. The compaction test was carried out on a 2 m thick disposal layer using a predetermined number of compaction passes.

2. Materials and Experimental Methods

The disposal material investigated in this study was obtained from an open-pit coal mine in Tanah Bumbu Regency, South Kalimantan, Indonesia. This material represents overburden excavated from the Warukin Formation, where interbedded sandstone, claystone, and coal seams constitute the dominant lithological sequence (Fig. 1). Claystone contains kaolinite, illite, and quartz-rich minerals and is susceptible to degradation when exposed to environmental changes, resulting in reduced physical and mechanical properties (Supandi et al., 2019). Quartz accounts for approximately 90% of the sandstone, making it the dominant mineral. Although quartz is the dominant mineral, the sandstone is described as fine to medium grained and less compact, resulting in relatively low rock strength with a uniaxial compressive strength of less than 1 MPa (Supandi et al., 2020). These lithological units constitute the primary overburden and interburden materials in the study area.

This study builds on previous research that combines field investigations and laboratory testing. Field testing consisted of undisturbed sampling using a Large Sampler Tube (LST) and in-situ bearing capacity testing using DCP. Undisturbed samples using LST were collected from the test line at depths of 0.3 m, 0.6 m, 0.9 m, 1.2 m, and 1.5 m. Subsequent testing was conducted in the company's laboratory to determine natural density (ND), moisture content (MC), and dry density (DD). DCP testing was also conducted near each test pit to obtain soil bearing capacity data for validation purposes.

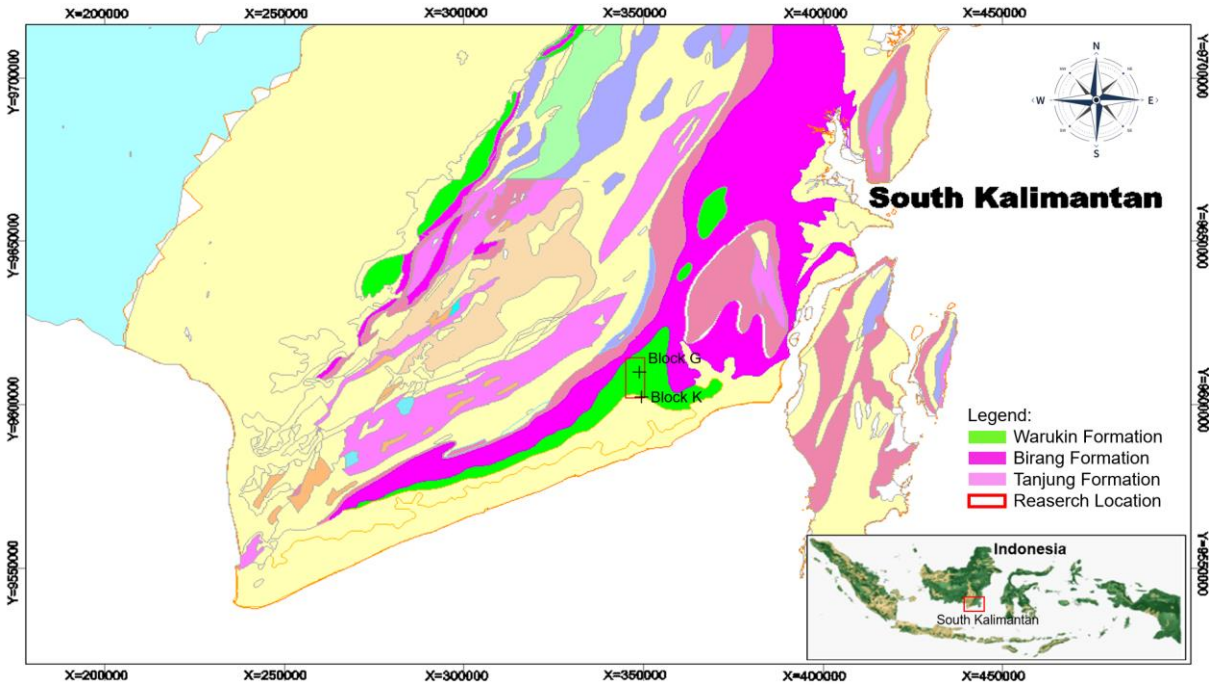


Fig. 1. Geological map and location of the compaction test area within the Warukin Formation, South Kalimantan, Indonesia, modified after (Fikri et al., 2022)

The previous study demonstrated that compaction behaviour is strongly influenced by lithology, particle size distribution, loading pressure, and compaction cycles, where stronger materials tend to exhibit lower deformation and particle crushing compared to weaker materials (Li et al., 2019; Bishwal et al., 2018). Undisturbed sampling was conducted on disposal areas with ages of 0-3 months, 6-12 months, and larger than 12 months, as well as on haul roads, to evaluate disposal material density resulting from natural compaction due to self-weight and repeated loading from haul truck traffic (Sidiq et al., 2025). In contrast, the present study focuses on disposal material that was mechanically compacted using a 20-ton compactor. Undisturbed sampling was performed in test pits constructed on disposal surfaces compacted with 0, 10, 20, 30, and 40 passes to quantify the effect of mechanical compaction on material density at depths of 0.3, 0.6, 0.9, 1.2, and 1.5 m (Fig. 2f).

The geometry of the compaction test lanes is illustrated in Fig. 2a. Each lane was approximately 7 m long and 2.2 m wide, corresponding to the effective drum width of the Caterpillar CS79B vibratory compactor. Adjacent lanes were separated by approximately 2.5 m, and a test pit approximately 1.2 m wide was excavated at the center of each lane for undisturbed sample collection (Fig. 2d). The compaction testing procedure was preceded by preparation of the disposal layers at the study area. First, overburden material was hauled by dump trucks and placed onto the prepared disposal surface (Fig. 2b). Second, the dumped material was levelled using a bulldozer to achieve a uniform lift height of approximately 2 m before mechanical compaction was applied (Fig 2c). Third, compaction lanes were established and compacted using a 20-ton compactor with predetermined numbers of passes (0, 10, 20, 30, and 40 passes) (Fig. 2e). Fourth, test pits were excavated along each compaction lane for undisturbed sampling at 0.3 m depth intervals (Fig. 2f). Finally, DCP tests were conducted adjacent to each test pit (Fig.2g). The overall testing sequence is illustrated in Fig. 2.

Undisturbed sampling was carried out following the same procedures applied in the previous study (Sidiq et al., 2025). The collected samples were subsequently transported to the company's internal laboratory for the determination of density in accordance with ASTM D2937 (2024).



Fig. 2. a) The compaction test lanes are illustrated, b) Dumping of overburden material, c) compaction process, d) the geometry of the compaction test lanes, e) compaction lanes, f) profile of the test pit wall where undisturbed sampling was carried out, and g) DCP testing

3. Results and Discussion

The DD increases with increasing MC up to the optimum moisture content (OMC); however, further increases in MC beyond the OMC result in a decrease in dry density of soil (Yilmaz et al., 2019; Sun et al., 2023). The laboratory test results for MC and DD are summarized in Table 1 for samples collected from disposal Block K and in Table 2 for samples collected from disposal Block G. Blocks G and K were selected to represent disposal materials with different lithological and excavation characteristics. The disposal material in Block G was derived from overburden loosened using a combination of blasting and free-digging methods and was dominated by claystone material. While at Block K consisted predominantly of sand overburden excavated mainly by free digging. Differences in material composition and excavation conditions were expected to influence the compaction response and density characteristics of the disposal material. The headers “K 0 Pass,” “K 10 Pass,” and subsequent labels in Table 1 indicate samples obtained from Block K at compaction lanes subjected to 0 passes (uncompacted condition) and increasing numbers of compactor passes. Similarly, the headers “G 0 Pass,” “G 10 Pass,” and subsequent labels in Table 2 represent samples collected from Block G under the same compaction conditions.

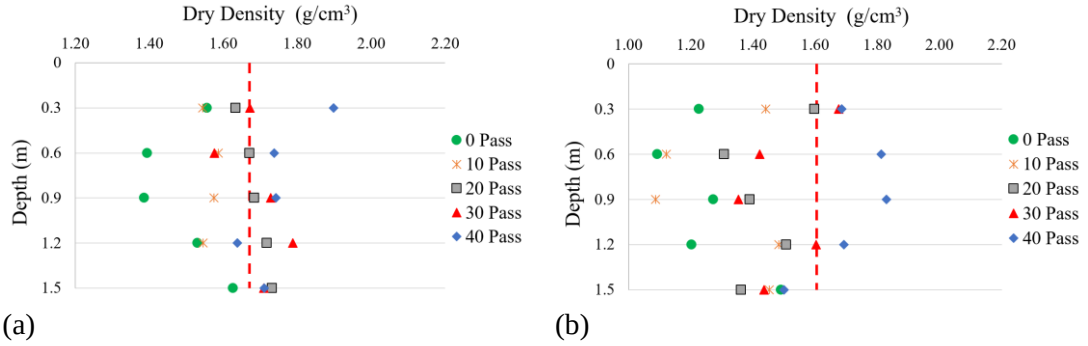
Table 1. Moisture content and dry density of disposal material at Block K

Depth (m)	K 0 Pass		K 10 Pass		K 20 Pass		K 30 Pass		K 40 Pass	
	MC (%)	DD g/cm^3	MC (%)	DD g/cm^3	MC (%)	DD g/cm^3	MC (%)	DD g/cm^3	MC (%)	DD g/cm^3
0.3	12.95	1.56	13.61	1.54	14.06	1.63	15.02	1.67	9.18	1.90
0.6	13.62	1.39	18.69	1.59	14.73	1.67	15.24	1.58	14.42	1.74
0.9	14.04	1.39	16.75	1.58	9.98	1.68	11.33	1.73	14.97	1.74
1.2	9.84	1.53	14.02	1.55	15.44	1.72	11.97	1.79	12.50	1.64
1.5	10.95	1.63	10.08	1.73	14.76	1.73	10.28	1.71	15.34	1.71

Table 2. Moisture content and dry density of disposal material at Block G

Depth (m)	G 0 Pass		G 10 Pass		G 20 Pass		G 30 Pass		G 40 Pass	
	MC (%)	DD g/cm^3	MC (%)	DD g/cm^3	MC (%)	DD g/cm^3	MC (%)	DD g/cm^3	MC (%)	DD g/cm^3
0.3	15.82	1.23	13.50	1.44	15.27	1.60	13.81	1.68	13.78	1.69
0.6	15.25	1.09	15.43	1.12	15.25	1.31	13.39	1.42	13.75	1.81
0.9	16.11	1.27	16.61	1.09	17.17	1.39	13.49	1.35	13.50	1.83
1.2	16.18	1.20	12.33	1.48	16.89	1.51	13.56	1.60	17.73	1.69
1.5	16.17	1.49	15.05	1.45	17.83	1.36	15.76	1.44	13.89	1.50

The results in Tables 1 and 2 were plotted as depth-density profiles (Fig. 3) to show how mechanical compaction affects dry density with depth. The maximum dry density (MDD) for mixed disposal materials from Block K was 1.671 g/cm³, and the MDD for materials from Block G was 1.605 g/cm³ (Sidiq et al., 2024). These MDD values are represented by dashed red lines in Fig. 3.



(a) (b)

Fig. 3. Correlation of dry density and depth, (a) disposal Block K, and (b) disposal Block G

Fig. 3 illustrates the variation of dry density with depth for each dump block under different numbers of compaction passes. Block K and Block G show the same pattern as the number of passes goes up; the dry density values go up as well, down to a depth of about 1.2 m. This observation indicates that dry density increases with the number of compactor passes, while the compaction effect decreases with increasing depth due to the attenuation of vibratory energy, resulting in an effective compaction depth of approximately 1.2 m for a 2 m disposal lift.

The DCP test results, converted to CBR values, were used to validate the dry density measurements (Sidiq et al., 2024). The conversion equation from DCP to CBR values refers to (Sidiq et al., 2025) (Eq. (1)):

$$Log\,(\mathrm{CBR}) = \alpha - \beta \mathrm{x}\ Log\,(\mathrm{DCP}) \quad (1)$$

Where α = intercept and $-\beta$ = slope from the graph of the relationship between DCP value and CBR value.

The combined plots of DD and CBR values at each depth along the compaction lanes in Block K are presented in Fig. 4, while corresponding results for Block G are shown in Fig. 5. In both figures, the orange line represents CBR values (%) and the black line represents dry density values.

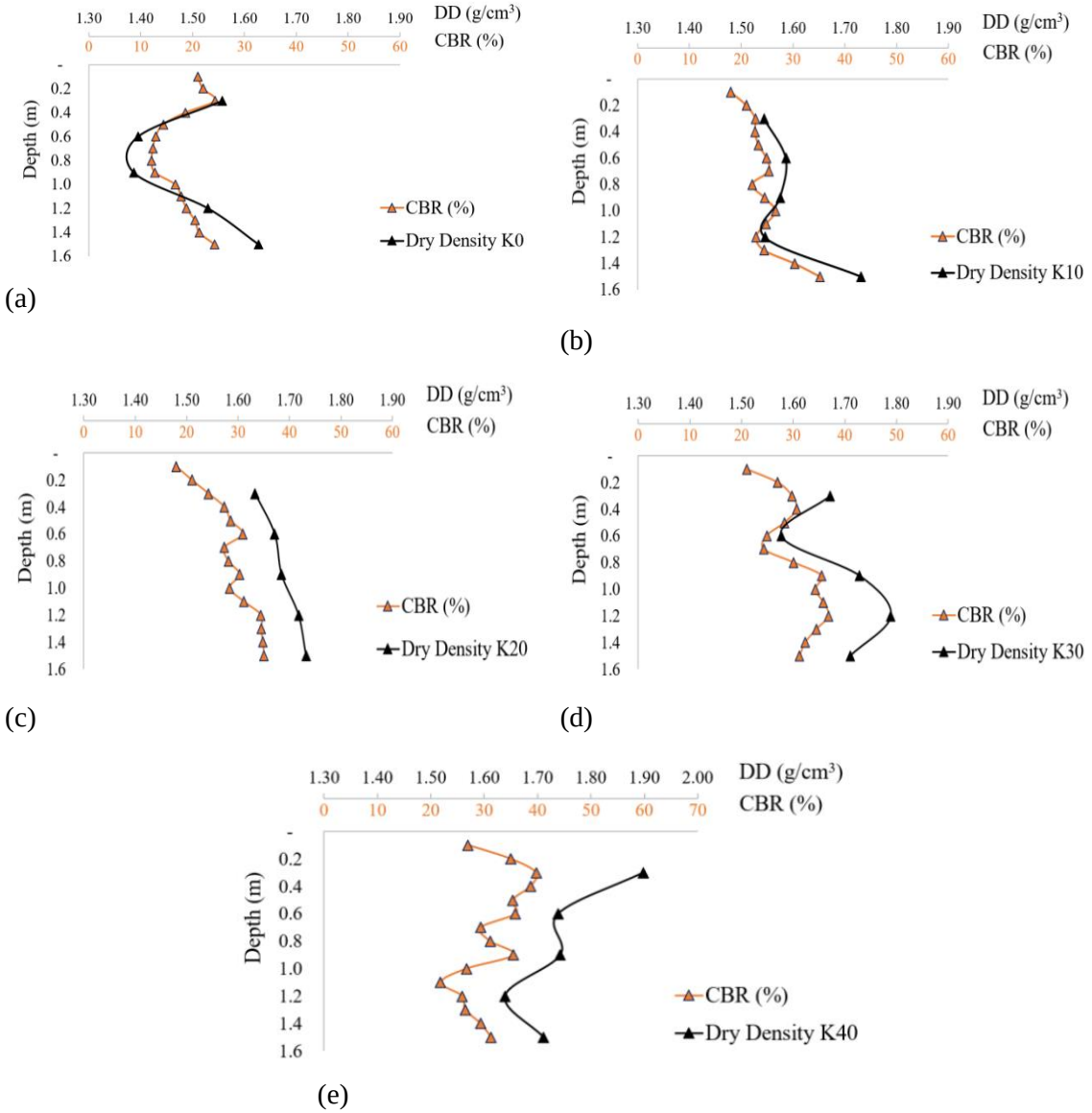


Fig. 4. Distribution of DD and CBR values at each depth along the compaction material disposal lines of Block K: a) 0 passes, b) 10 passes, c) 20 passes, d) 30 passes, and e) 40 passes

Fig. 4 shows that the distribution patterns along depth for DD and CBR values are strongly correlated. A decrease in DD is consistently accompanied by a decrease in CBR, and vice versa. At a depth of 0.3 m, dry density of disposal material under 0-pass conditions was 1.56 g/cm³, corresponding to a CBR value of 24%. Dry density increased to 1.90 g/cm³ after compaction with 40 passes with a corresponding CBR value of 39%. This confirms that increasing the number of compactor passes significantly enhances material density and bearing capacity near the surface in disposal Block K.

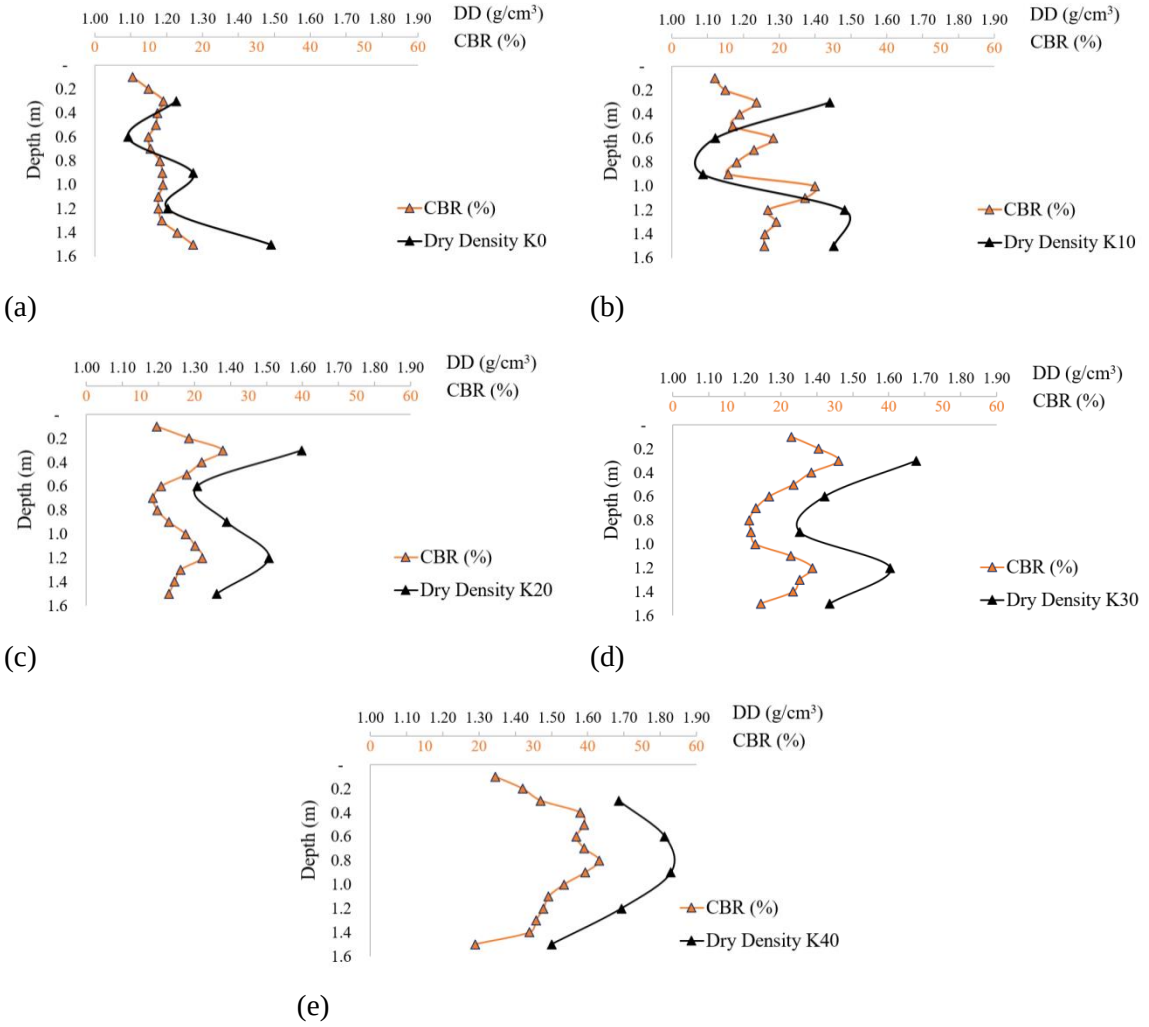


Fig. 5. Distribution of DD and CBR values at each depth along the compaction material disposal lines of disposal Block G: a) 0 passes, b) 10 passes, c) 20 passes, d) 30 passes, and e) 40 passes

Block G (Fig. 5) shows a similar relationship between DD and CBR. DD value increased from 1.23 g/cm³ (CBR = 12%) under 0-pass conditions to 1.69 g/cm³ (CBR = 31%) after 40 passes at a depth of 0.3 m. The greater number of compaction passes makes the disposal material in Block G denser and stronger, especially at shallow depths.

Referring to compaction standards for dump materials used for infrastructure, a minimum of 95% MDD is commonly adopted as an acceptance criterion (Niphadkar, 2016). Based on this criterion, the target minimum dry density for mixed disposal material is 1.58 g/cm³ for Block K and 1.525 g/cm³ for Block G (Sidiq et al., 2024). To determine the optimal number of compactor passes required to achieve this minimum dry density. The dry density data from Tables 1 and 2 were plotted against laboratory compaction test (LCT) curves (Sidiq et al., 2025), as shown in Fig. 6 for Block K and Fig. 7 for Block G.

In Block K, the minimum target dry density (≥ 95% MDD) was achieved after at least 20 passes (Fig. 6c). Further increases in the number of passes resulted in continued increases in dry density, with moisture content remaining below the optimum moisture content, up to 40 passes (Fig. 6de).

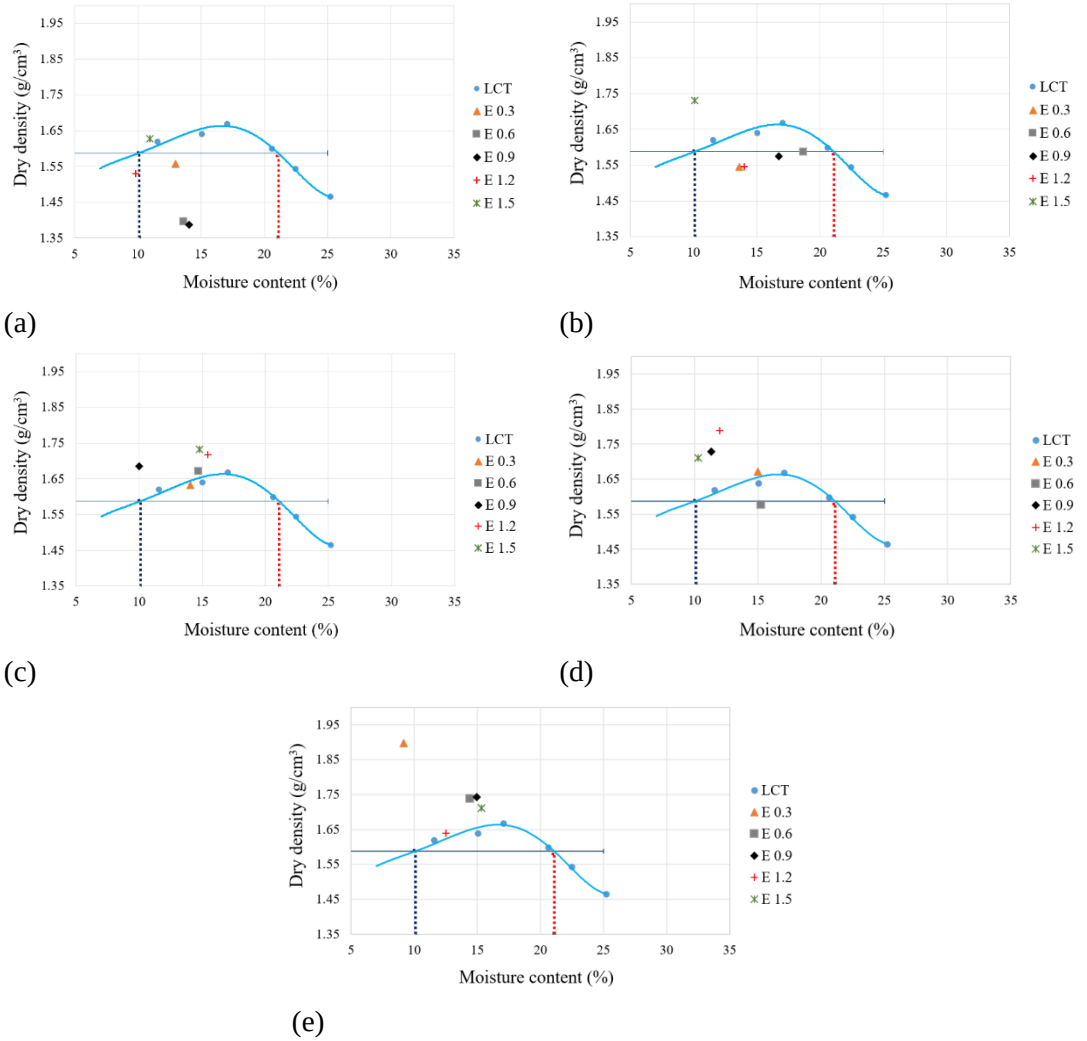
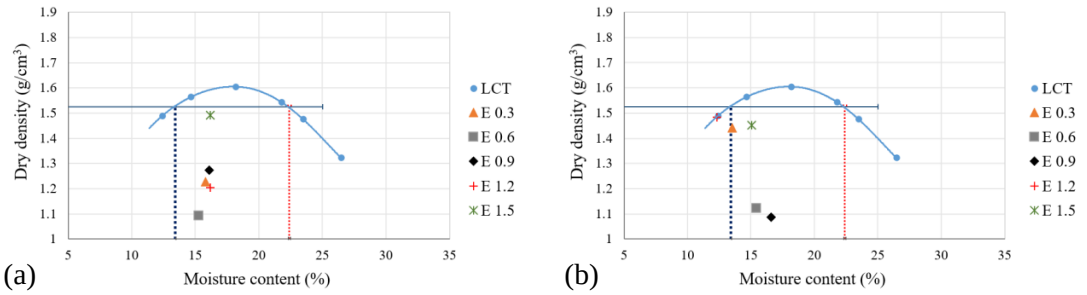


Fig. 6. Dry density distribution with depth along compaction lanes in Disposal Block K: a) 0 passes, b) 10 passes, c) 20 passes, d) 30 passes, and e) 40 passes

In contrast, for Block G, achieving the minimum target dry density (≥95% MDD) after 20 compactor passes was only effective at a depth of 0.3 m (Fig. 7c). Increasing the compaction effort resulted in a gradual improvement in dry density at greater depths. As shown in Fig. 6e, increasing the number of compactor passes to 40 resulted in substantial density improvement throughout the disposal layer. However, the minimum target dry density was achieved only up to a depth of approximately 1.2 m. Although some densification was still observed at 1.5 m depth, the resulting dry density remained below the target value, indicating that the effective compaction depth of the 20-ton compactor was limited to approximately 1.2 m under the tested field conditions.



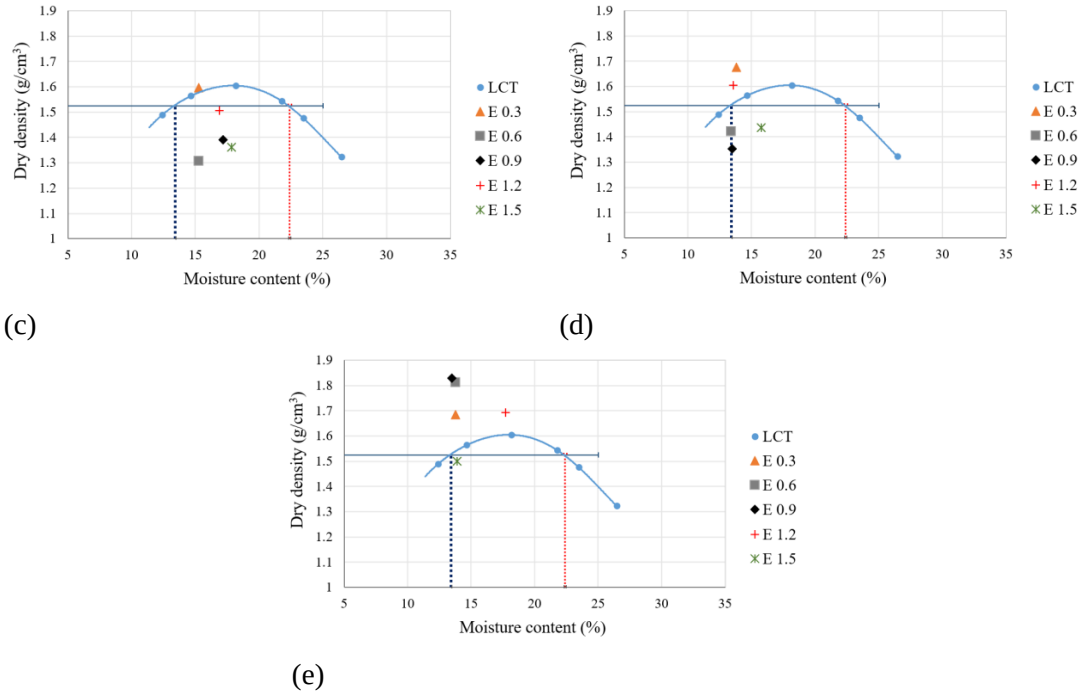


Fig. 7. Dry density distribution with depth along compaction lanes in Disposal Block G: a) 0 passes, b) 10 passes, c) 20 passes, d) 30 passes, and e) 40 passes

The relationship between compaction variables and soil response parameters was further evaluated using linear regression analysis. Effective compaction depth was determined based on the combined interpretation of slope values and coefficients of determination (R^2), which indicate the strength of the linear relationship between the number of passes and dry density. A sharp reduction in slope and low R^2 values at a given depth indicate that additional compaction passes no longer produce meaningful increases in dry density, thereby defining the effective compaction limit (Soltani et al., 2021; Li et al., 2021).

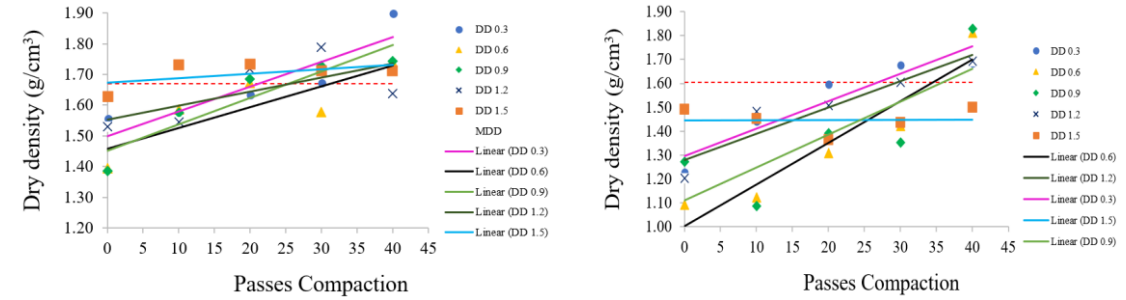
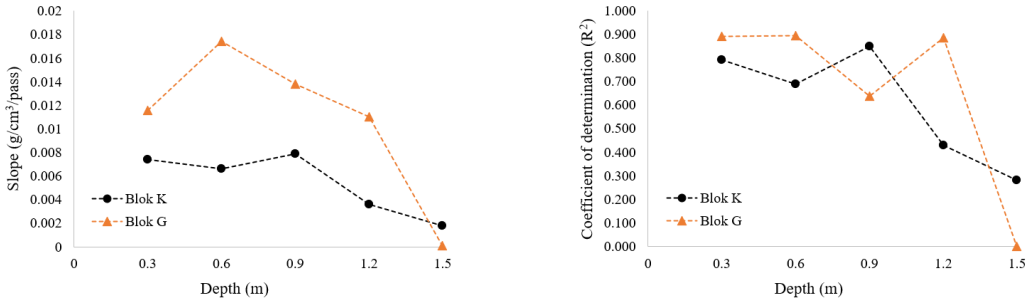


Fig. 8. Relationship between dry density and number of passes at each depth: a) Disposal Block K and b) Disposal Block G

Linear regression analysis was performed for each test depth (0.3-1.5 m) by plotting dry density against the number of compactor passes for disposal materials in Blocks K and G to determine the slope coefficient and R^2 values, as shown in Fig. 8.

Fig. 8 shows that increasing the number of passes generally results in MDD values. However, at a depth of 1.5 m, DD value remains nearly constant even up to 40 passes, indicating a negligible compaction effect at this depth. The dashed red line represents MDD obtained from laboratory

compaction tests. To further identify the effective compaction depth, slope coefficient and R^2 values derived from Fig. 8 were plotted against depth, as shown in Fig. 9.



(a) (b)

Fig. 9. Optimum depth of compaction based on a) slope coefficient values and b) coefficients of determination (R^2) for Disposal Blocks K and G

Fig. 9a shows that the best depth for a 20-ton compactor in compacting mixed disposal material in Block K is up to about 0.9 m, and then quickly loses its effectiveness after 1.2 m. The big drop in slope coefficient values at depths deeper than 1.2 m suggests that compaction energy is no longer working, which means that the best depth for compaction is less than 1.2 m. In Block G, the most effective compaction happens at a depth of up to about 0.6 m, but the effects of compaction can still be seen down to a depth reaching 1.2 m, as shown by the higher slope values compared to Block K. Fig. 9b backs this up further, with R^2 values of 0.850 at 0.9 m depth for Block K and 0.886 at 1.2 m depth for Block G, showing strong linear relationships between the number of passes and dry density within these depth ranges.

4. Conclusions

This study presents a concept for investigating the compaction effect of disposal materials using a mechanical compactor. Material sampling was carried out in various numbers of passes, from 0 to 40 passes, at depths of 0 to 1.5 m. Effective compaction depth was determined based on the combined interpretation of slope coefficient values and coefficients of determination (R^2), which indicate the strength of the linear relationship between the number of passes and dry densities. CBR values obtained from DCP testing were measured adjacent to the undisturbed sampling points to verify the correlation between dry density and compaction performance.

The effectiveness of mechanical compaction with a 20-ton compactor in increasing the density of disposal material mixture of sand-clay was demonstrated through field testing at disposal Blocks K and G using a lift height of 2 m. In disposal Block K, the minimum target dry density (≥ 95% MDD) was achieved with at least 20 passes, and dry density continued to increase with additional passes while moisture content remained below the optimum value. However, the disposal material in Block G needed more compaction. The minimum dry density was only reached after at least 40 passes, and the compaction effect only worked down to a depth of about 1.2 m out of the total tested depth of 1.5 m.

Variations in DD values were consistently validated by corresponding changes in CBR values obtained from DCP testing, indicating a strong correlation between density and strength response. Thus DCP testing can be effectively utilized as a practical field method for evaluating the relative compaction level of disposal material, particularly for rapid assessment and quality control purposes.

Although this study focused on density improvement through mechanical compaction, future studies should investigate the corresponding changes in shear strength parameters, including cohesion (C) and friction angle (φ), to better evaluate their influence on disposal slope stability.

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Author Contributions

Hidayatullah Sidiq: conceptor, methodology, data acquisition, lab analysis, and interpretation of data, as drafting the article. Budi Sulistianto: supports the review of research design, concepts, data acquisition, lab tests, and interpretation. Tri Karian: supports the review of research design, acquisition. Supandi: supports the review of research design, acquisition, lab tests. Eriezzha A. H.: scientific editing, and language editing of the manuscript.

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Declaration of Competing Interest

The authors declare no conflict of interest. Although PT Borneo Indobara supported the field investigation and provided financial assistance, the company had no role in the study design, data collection, data analysis, interpretation of the results, and manuscript preparation.

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