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Influence of Rammer Mass and Blow Count on Compaction Characteristics and CBR Values of Gravel Materials

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Abstract

This study investigates the influence of increased laboratory compaction energy on the engineering properties of gravel materials used in road construction. Compaction energy was varied by altering rammer mass (2.5 kg, 4.5 kg, 6.5 kg, and 8.5 kg), number of blows per layer (27, 43, 62, 82, and 100), and drop heights of 300 mm and 450 mm using a standard CBR mould with five layers. The effects of these variations were evaluated through moisture–density relationships, California Bearing Ratio (CBR), particle size distribution (PSD), and Atterberg limit tests.

Results indicate that increasing compaction energy generally improves maximum dry density (MDD) and CBR values up to an optimum level, beyond which further energy application results in strength reduction. The highest MDD (1868 kg/m³) was achieved using a 6.5 kg rammer at 62 blows per layer, while the maximum CBR value (41.1%) was obtained using an 8.5 kg rammer at 27 blows per layer. Optimum moisture content (OMC) decreased consistently with increasing compaction energy. Excessive compaction energy led to significant particle breakage, increased fines content, and reduction in both MDD and CBR values.

The findings demonstrate that compaction energy must be optimized rather than maximized to achieve superior mechanical performance of gravel materials. Over-compaction may degrade particle structure and negatively affect strength characteristics, emphasizing the need for controlled compaction practices in road construction.

Keywords: Compaction efforts, CBR values, Number of blows, Rammer weights, Number of repetitions, Gravel materials

1. Introduction and Literature Review

Gravel materials are widely used in road construction due to their favorable mechanical properties, relatively low cost, and widespread availability. These materials typically consist of a mixture of coarse gravel particles, sand fractions, and varying amounts of fine-grained soils. Because of this heterogeneous composition, gravel materials can provide adequate load-bearing capacity and structural stability when properly compacted, making them suitable for use in embankments, improved subgrades, sub-base layers, and base courses in flexible pavement systems (Chen et al., 2018; Aweda et al., 2020). The engineering performance of these pavement layers depends strongly on the degree of compaction achieved during construction, as compaction improves particle interlocking, reduces void spaces, and increases the stiffness and shear strength of the material (Das, 2010).

Compaction is the mechanical process of densifying soil by reducing the volume of air voids through the application of external mechanical energy. Laboratory compaction tests are commonly used to determine the relationship between moisture content and dry density, allowing engineers to identify the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) required to achieve adequate field compaction. The earliest standardized laboratory compaction procedure was introduced by Ralph R. Proctor in 1933 and is commonly referred to as the Standard Proctor test, which uses a 2.5 kg rammer dropped from a height of 300 mm to compact soil in layers (Das, 2010; BS 1377, 1990). With the increasing demand for stronger pavement structures capable of supporting heavier traffic loads, the Modified Proctor test was later developed, employing a heavier 4.5 kg rammer dropped from a height of 450 mm, resulting in significantly higher compaction energy.

Several alternative laboratory procedures have also been developed to simulate higher field compaction energies. For example, the TEX-113-E method used by the Texas Department of Transportation applies a higher number of blows per layer to evaluate the compaction characteristics of granular base materials under more intensive energy conditions. Similarly, European compaction standards such as EN 13286 utilize heavier rammers and greater drop heights to simulate the effects of modern heavy compaction equipment used in pavement construction. These developments reflect the need to better understand the behavior of granular materials under increasing compaction energy levels.

Previous studies have shown that increasing compaction energy generally improves the density and strength characteristics of granular materials. Chen et al. (2018) reported that higher compaction energy enhances particle interlocking and reduces void ratios, resulting in improved mechanical performance of granular soils. Similarly, Basack et al. (2021) observed that increased compaction effort can significantly improve the stiffness and load-bearing capacity of pavement materials. The California Bearing Ratio (CBR) test is widely used to evaluate the strength of compacted soils used in pavement layers, and numerous studies have demonstrated that CBR values tend to increase with increasing compaction energy due to improved particle contact and resistance to deformation (Beddu et al., 2018; Nkwanzi et al., 2025).

Despite these well-established relationships, recent research has highlighted that excessive compaction energy may not always produce beneficial results, particularly for crushable granular soils. When granular materials are subjected to high stresses during compaction, individual particles may fracture or abrade, producing smaller particles and increasing the proportion of fines. This process, known as particle breakage, can significantly alter the particle size distribution and influence the mechanical behavior of the soil (Hardin, 1985). Particle breakage modifies the contact structure between soil grains and may affect important engineering properties such as density, shear strength, compressibility, and permeability (Zhang & Buscarnera, 2015).

In gravel materials used for pavement construction, the coarse particle skeleton plays a crucial role in resisting applied loads and maintaining structural stability. Moderate particle breakage may improve densification by filling void spaces between larger particles, thereby enhancing packing efficiency. However, excessive particle crushing may disrupt the coarse particle framework and generate excessive fines, which can reduce inter-particle friction and weaken the load-bearing capacity of the material (Chen et al., 2018; Youventharan et al., 2021). Consequently, excessive compaction energy may lead to deterioration of engineering performance despite the application of greater mechanical effort.

Although numerous studies have examined the relationship between compaction energy and soil density or strength characteristics, relatively few investigations have systematically evaluated the combined effects of rammer mass and number of blows on particle breakage and strength behavior of gravel materials. Most previous research has focused on conventional compaction procedures such as the Standard Proctor and Modified Proctor tests, which represent relatively narrow ranges of compaction energy. As modern road construction increasingly involves heavy compaction equipment capable of delivering significantly higher compaction energies, the potential effects of excessive compaction energy on particle degradation and engineering performance remain insufficiently understood.

Therefore, this study investigates the influence of varying rammer mass and number of blows on the compaction characteristics, strength behavior, and gradation changes of gravel materials used in road construction. A wide range of compaction energies was applied, extending from values below Standard Proctor energy to levels significantly exceeding Modified Proctor energy. The effects of these variations were evaluated through laboratory testing including moisture–density relationships, California Bearing Ratio (CBR), particle size distribution (PSD), and Atterberg limits.

The primary objective of this research is to determine whether an optimum compaction energy threshold exists beyond which additional compaction effort may result in excessive particle breakage and deterioration of engineering performance. By integrating compaction characteristics, strength behavior, and gradation changes, this study aims to provide improved understanding of the influence of compaction energy on gravel materials used in pavement construction and to contribute to more effective compaction practices in road engineering.

2. Methodology

2.1 Research Design

This study adopted a controlled laboratory experimental design to investigate the influence of varying compaction energy levels on the engineering properties of gravel materials used in road construction. Compaction energy was systematically varied by modifying rammer mass, drop height, and number of blows per layer while maintaining constant mould volume and number of layers.

All laboratory testing procedures were conducted in accordance with BS 1377 (1990) and MoW (2000) standards for soil testing for civil engineering purposes.

2.2 Materials and Sample Preparation

Gravel materials were obtained from Idugumbi borrow pit located in Mbeya Region, Tanzania. Samples were excavated at depths between 2 m and 3 m to minimize surface contamination and variability. The collected materials were transported to the Civil Engineering Materials Laboratory at Mbeya University of Science and Technology.

Figure 1: Photo of excavated materials at borrow pit (left) and air dried at lab (right)

Prior to testing, the samples were air-dried and processed according to BS 1377 (1990) procedures. Initial characterization of the material included Particle Size Distribution (PSD) by sieve analysis, Atterberg limits (Liquid Limit, Plastic Limit, and Plasticity Index), Moisture–density relationship and California Bearing Ratio (CBR) test. Based on the AASHTO classification system (AASHTO, 1986), the material was classified as A-2-6 (clayey gravel). Figure 1 shows photos of gravel materials sourced from the borrow pit and material process at laboratory drying yard.

2.3 Compaction Energy Program

Compaction energy was varied using four rammer masses which are 2.5 kg (drop height = 300 mm), 4.5 kg (drop height = 450 mm), 6.5 kg (drop height = 450 mm) and 8.5 kg (drop height = 450 mm). All specimens were compacted in a standard CBR mould of volume 0.002242 m³ using five layers. The number of blows per layer was varied as 27 blows, 43 blows, 62 blows, 82 blows and 100 blows. This experimental program enabled the simulation of compaction energies ranging from below Standard Proctor to significantly above Modified Proctor levels (BS 1377, 1990).

After compaction, the Moisture–density relationships were determined for each energy level, CBR tests were conducted on specimens compacted at their respective optimum moisture contents and soaked for four days in accordance with MoW (2000) and Compacted materials were air-dried and subjected to sieve analysis and Atterberg limit testing to evaluate gradation and plasticity changes. The compaction energy per unit volume was calculated using equation 1. The calculated compaction energies for all rammer weights and blow counts are presented in Table 1.

$$E = \frac{R * g * H * B * N}{V} \qquad 1$$

Where: E = Compaction energy (kJ/m³), R = Rammer mass (kg), g = Acceleration due to gravity (9.81 m/s²), H= Drop height (m), B = Number of blows per layer, N = Number of layers (5) and V = Mould volume (0.002242 m³).

Table 1: Consolidated Compaction Energy Table (rammer weight, blows, energy kJ/m³)

Blows per Layer	2.5 kg (300 mm)	4.5 kg (450 mm)	6.5 kg (450 mm)	8.5 kg (450 mm)
27	443	1,196	1,727	2,258
43	706	1,904	2,750	3,595
62	1,018	2,745	3,967	5,190

82	1,345	3,629	5,247	6,866
100	1,641	4,425	6,396	8,366

2.4 Reference Energy Levels for Comparison

For benchmarking purposes, the calculated compaction energies were compared with conventional laboratory compaction standards which are Standard Proctor energy ≈ 592 kJ/m³ (BS 1377, 1990) and Modified Proctor energy ≈ 2,700 kJ/m³ (BS 1377, 1990). From Table 1, The 2.5 kg rammer at 43 blows (706 kJ/m³) slightly exceeds Standard Proctor energy. The 4.5 kg rammer at 62 blows (2,745 kJ/m³) closely approximates Modified Proctor energy. Energy levels exceedingly approximately 4,000–5,000 kJ/m³ represent high to very high compaction efforts beyond conventional standards.

This wide range of compaction energy allowed evaluation of both conventional densification behavior and the effects of excessive compaction energy on particle degradation and mechanical performance.

2.5 Particle Breakage Assessment and Breakage Index Formulation

Gravel materials subjected to high compaction energy may experience particle crushing, resulting in changes in gradation and mechanical behavior. Particle breakage alters the inter-particle contact structure, increases fines content, and may significantly influence density and strength characteristics (Chen et al., 2018; Zhang & Buscarnera, 2015). To quantify the extent of particle degradation induced by varying compaction energy levels, a breakage index approach was adopted.

2.5.1 Determination of Particle Size Distribution Before and After Compaction

For each compaction energy level, the compacted specimens were air-dried and subjected to sieve analysis in accordance with BS 1377 (1990). The resulting post-compaction gradation curves were compared with the original (pre-compaction) gradation curve to evaluate changes in particle size distribution. Particular attention was given to the increase in percentage passing 0.075 mm sieve (fines content), changes in intermediate particle sizes and overall shift of the gradation curve.

2.5.2 Relative Breakage Index (Br)

The extent of particle breakage was quantified using the **Relative Breakage Index (Br)** proposed by Hardin (1985), which has been widely applied in crushable soil mechanics (Zhang & Buscarnera, 2015; Chen et al., 2018). The relative breakage index is defined as indicated in equation 2.

$$\mathrm{B}_r = \frac{\mathrm{B}_t}{\mathrm{B}_p} \qquad 2$$

Where: Br = Relative breakage index, Bt = Total breakage (area between initial and final gradation curves) and Bp = Breakage potential (area between initial gradation curve and a vertical line at 0.075 mm sieve size)

(a) Total Breakage (Bt)

Total breakage represents the area between the initial particle size distribution curve and the post-compaction curve on a semi-logarithmic plot as indicated in equation 3.

$$\mathrm{Bt} = \int (\mathrm{F}_{\mathrm{after}} - \mathrm{F}_{\mathrm{before}})\, d(\log \mathrm{D}) \qquad 3$$

Where: $\mathrm{F}_{\mathrm{before}}$ = Percent finer before compaction, $\mathrm{F}_{\mathrm{after}}$ = Percent finer after compaction, D = Particle diameter

(b) Breakage Potential (Bp)

Breakage potential represents the maximum possible breakage that could occur, defined as the area between the initial gradation curve and the line representing complete crushing to the minimum particle size considered (0.075 mm). The relative breakage index ranges from Br = 0 indicating no particle breakage and Br = 1 indicating complete breakage potential achieved

2.5.3 Simplified Breakage Indicator (ΔFines)

In addition to the relative breakage index, a simplified indicator of particle degradation was evaluated by calculating the increase in fines content as in equation 4 and relative breakage ratio as in equation 5.

$$\Delta F = F_{after} - F_{before} \qquad 4$$

Where: ΔF = Increase in percentage passing 0.075mm, F_{before} = Initial fines content (%), F_{after} = Fines content after compaction (%)

$$Br\ (\%) = \left(\frac{F_{after} - F_{before}}{F_{after}}\right) x100 \qquad 5$$

This simplified parameter provides a practical measure of compaction-induced crushing and was used to correlate breakage with compaction energy, MDD, and CBR values. In granular materials, moderate breakage may improve densification and interlocking, whereas excessive breakage can increase fines content, reduce permeability, lower shear strength and decrease CBR values (Chen et al., 2018; Zhang & Buscarnera, 2015). The fines before and after compaction for each rammer weight and number of blows are presented in table 2.

Table 2: Consolidated fine particles vs compaction energy (before and after)

Blows	**2.5kg**		**4.5kg**		**6.5kg**		**8.5kg**	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
27	13.98%	17.02%	13.98%	19.96%	13.98%	21.43%	13.98%	22.04%
43	13.98%	18.14%	13.98%	24.99%	13.98%	25.21%	13.98%	27.34%
62	13.98%	26.04%	13.98%	30.48%	13.98%	34.80%	13.98%	46.45%
82	13.98%	28.26%	13.98%	33.31%	13.98%	35.34%	13.98%	46.76%
100	13.98%	35.14%	13.98%	40.30%	13.98%	43.00%	13.98%	45.21%

2.6 Data Analysis

The relationships between compaction energy and Maximum Dry Density (MDD), Optimum Moisture Content (OMC), California Bearing Ratio (CBR), Fines content and Breakage index were evaluated to determine the existence of an optimal compaction energy threshold beyond which mechanical performance deteriorates.

3. Results and Discussion

3.1 Characterization of the Gravel Material

The gravel material sourced from Idugumbi borrow pit was classified as **A-2-6 (clayey gravel)** according to AASHTO standards (Table 3) (AASHTO, 1986). Particle size distribution analysis indicated approximately 63% gravel, 23% sand, and 14% fines passing the 0.075 mm sieve.

Table 3: Classification of Soil Materials (AASHTO)

Source materials	Physical properties	AASHTO Classification	% Fines	% Sand	% Gravel
Gravel material	Reddish Brown colour soil	A-2-6 Clayey Gravel	13.98	23.26	62.75

The fines fraction exhibited a Liquid Limit (LL) of 34%, Plastic Limit (PL) of 17%, and Plasticity Index (PI) of 17%, indicating moderate plasticity above the commonly recommended limit of 12% for gravel base materials (Das, 2010). These baseline physical properties suggest the material's behavior under compaction may be influenced by the plastic fines content. The gradation curve of the original gravel material is presented in **Figure 2**, illustrating the proportion of gravel, sand, and fines.

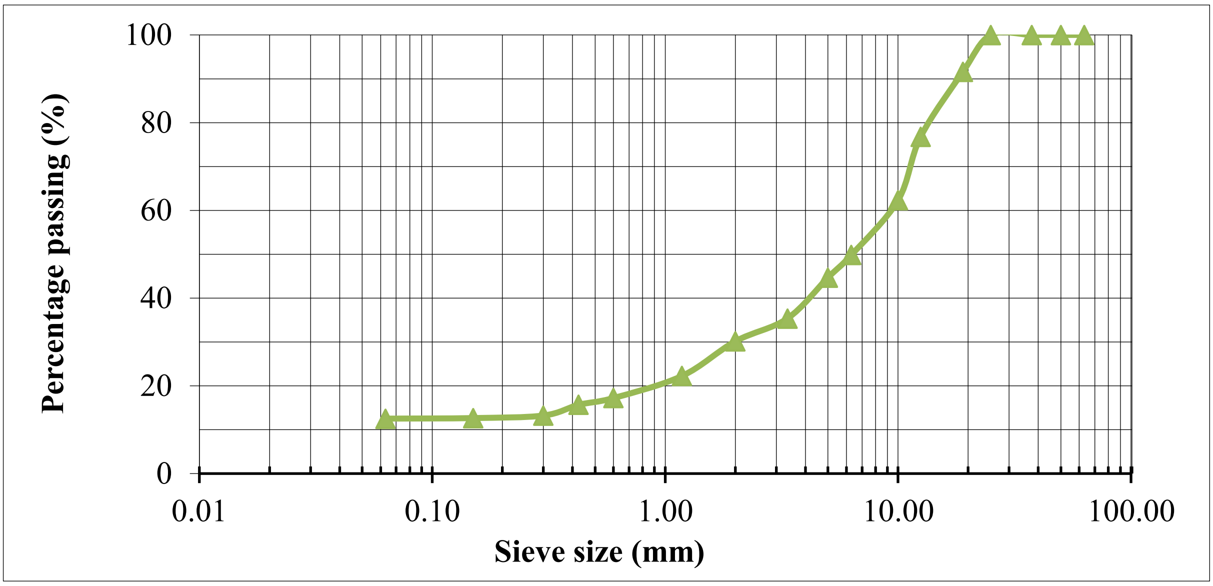

Figure 2: Gradation curve of the original gravel material

The baseline Modified Proctor compaction test produced a Maximum Dry Density (MDD) of 1860 kg/m³ and an Optimum Moisture Content (OMC) of 10.5% (Figure 3). The soaked California Bearing Ratio (CBR) at 95% MDD was 21%, providing a reference point for evaluating the effects of increased compaction energy.

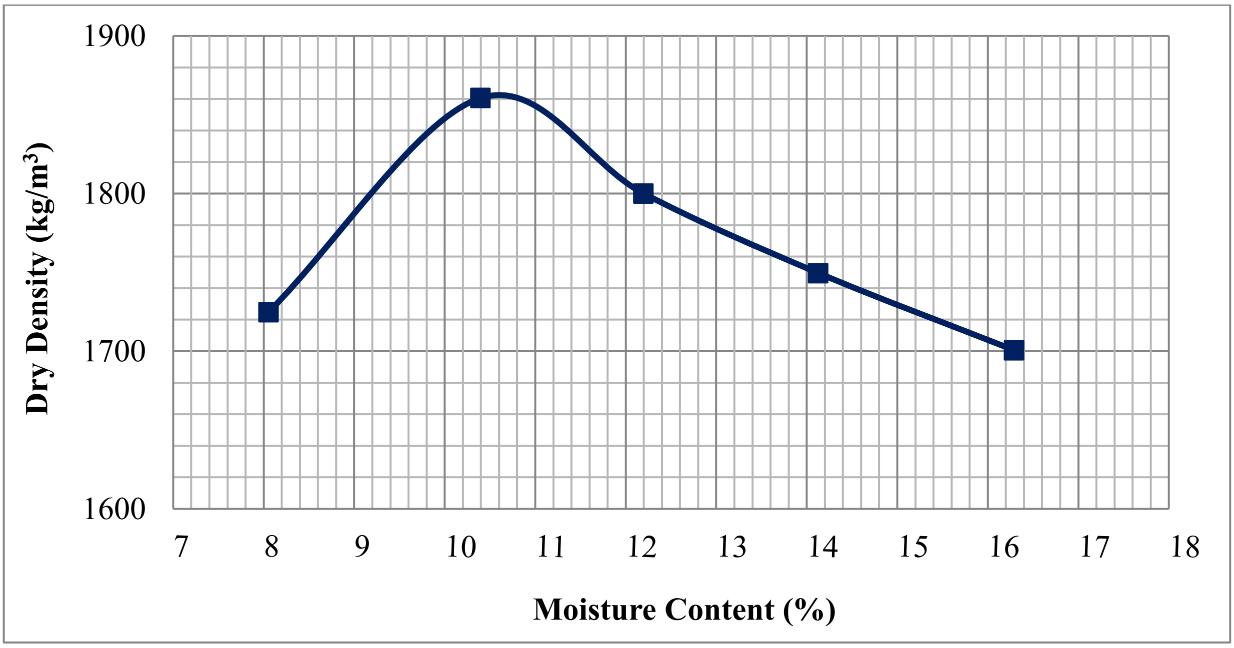

Figure 3: Baseline Compaction Curves of Soil Materials

3.2 Effect of Compaction Energy on Maximum Dry Density

Compaction energy was varied from 443 kJ/m³ to 8,366 kJ/m³, covering energy levels below Standard Proctor up to significantly above Modified Proctor (Table 1) (BS 1377, 1990). The results indicate that MDD increased with compaction energy up to an optimal range, after which further energy application resulted in reduced dry density.

For the 2.5 kg rammer, MDD increased progressively with blow count, reaching a maximum of 1800 kg/m³ at 100 blows. The 4.5 kg and 6.5 kg rammers exhibited steady MDD increases up to 62 blows, producing peak MDD values of 1860 kg/m³ and 1868 kg/m³, respectively (**Figure 4**). Beyond these blow counts, MDD decreased, indicating over-compaction. For the 8.5 kg rammer, the maximum MDD (1810 kg/m³) occurred at 27 blows, and further increase in blows led to continuous density reduction. This reduction at very high compaction energies is attributed to excessive particle breakage, increased fines content, and disruption of the coarse particle skeleton (Chen et al., 2018).

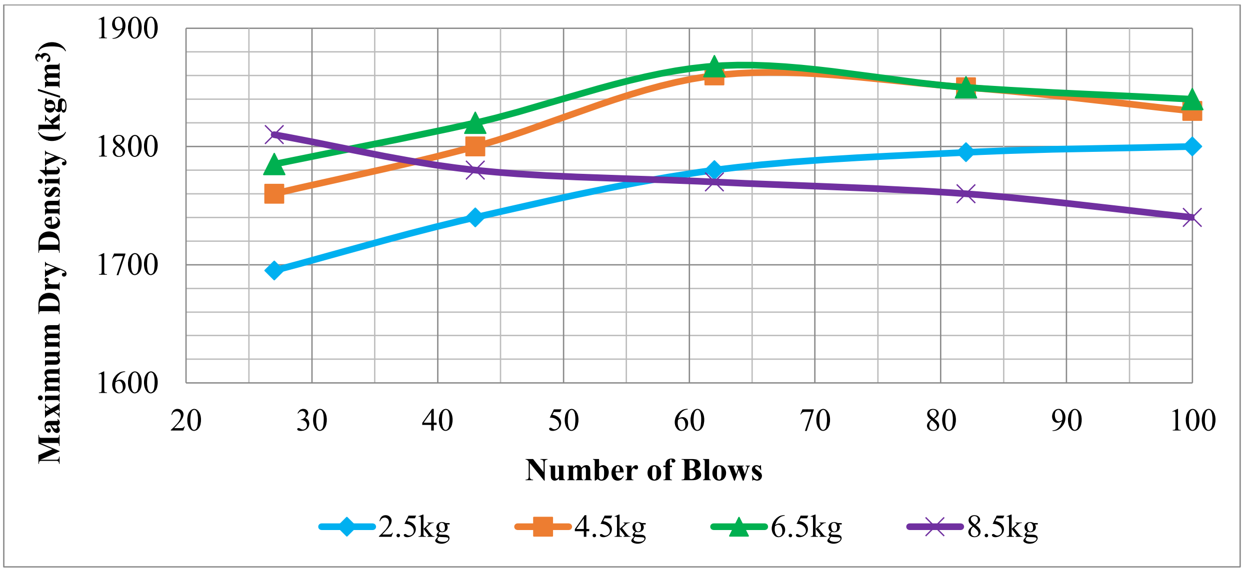

Figure 4: MDD vs number of blows for all rammer weights

3.3 Effect of Compaction Energy on Optimum Moisture Content

The OMC decreased consistently with increasing compaction energy for all rammer weights (Figure 5). Higher mechanical energy allowed soil particles to overcome internal friction more efficiently, reducing the water required to lubricate particle rearrangement (Das, 2010). While reduced OMC indicates improved packing efficiency, excessive energy may still compromise structural stability due to particle degradation, particularly at high-energy levels for the 8.5 kg rammer.

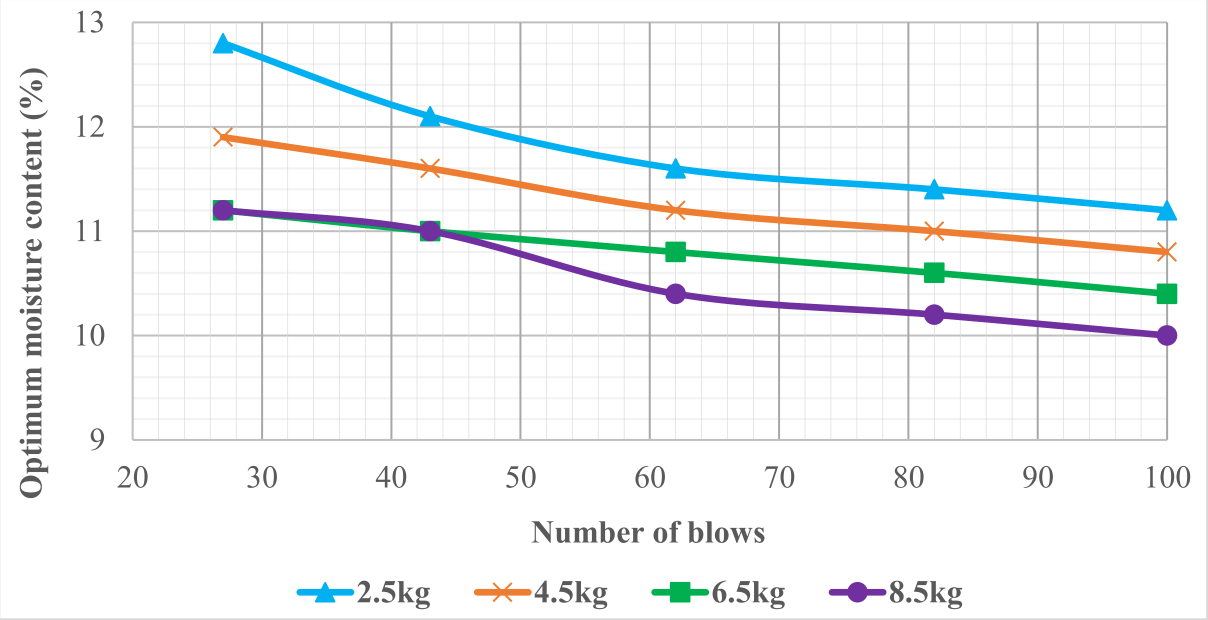

Figure 5: OMC vs number of blows for all rammer weights

3.4 Effect of Compaction Energy on California Bearing Ratio

CBR values exhibited a non-linear response to compaction energy (Figure 6). For the 2.5 kg and 4.5 kg rammers, CBR increased with energy up to 82 blows, yielding maximum values of 28.8% and 30.2%, respectively. For the 6.5 kg rammer, the peak CBR (35.2%) occurred at 43 blows. These increases reflect densification, particle interlocking, and increased shear resistance (Basack et al., 2021).

In contrast, the 8.5 kg rammer produced a maximum CBR of 41.1% at 27 blows, and further increases in blows reduced CBR values, indicating that excessive compaction energy induced particle degradation and higher fines content, reducing internal friction and structural strength (Beddu et al., 2018; Zhang & Buscarnera, 2015). These findings highlight the importance of optimizing compaction energy rather than maximizing it.

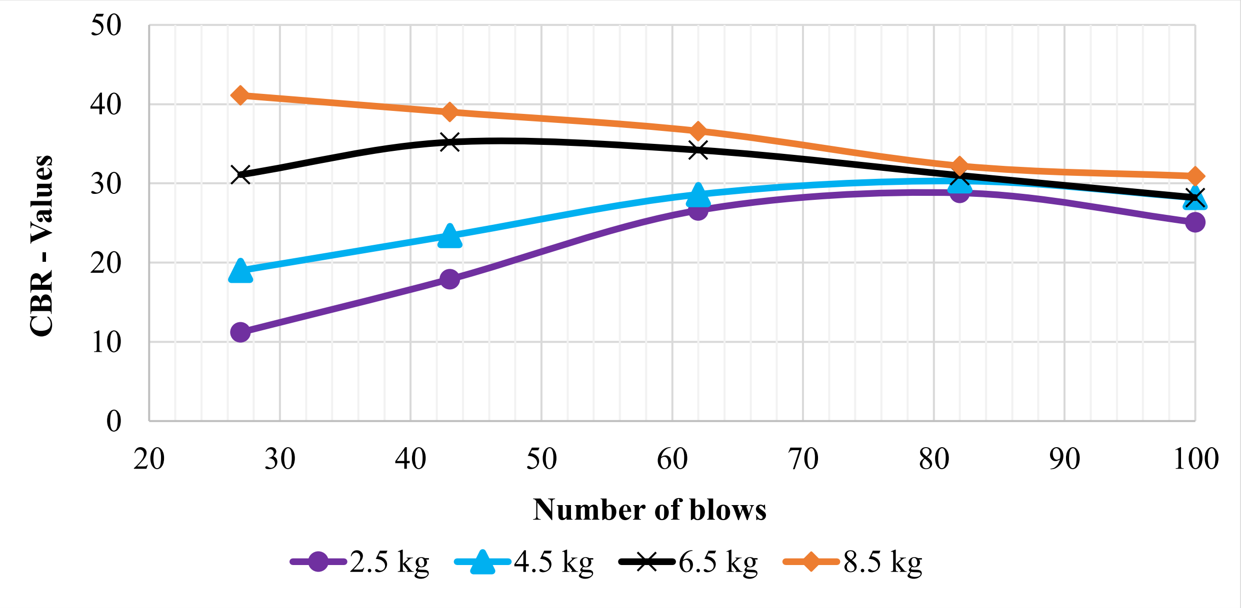

Figure 6: CBR vs number of blows for all rammer weights

3.5 Particle Breakage and Gradation Changes

Sieve analyses conducted after compaction revealed progressive changes in the particle size distribution with increasing compaction energy. The most noticeable change was the increase in fines passing the 0.075 mm sieve, indicating that particle breakage occurred during the compaction process. As shown in Table 2, the fines content increased substantially from the initial value of approximately 13.98% to values exceeding 40% at the highest compaction energy levels.

At low compaction energy levels, only minor increases in fines were observed, suggesting that the compaction process was mainly governed by particle rearrangement and void reduction rather than particle crushing. Under these conditions, the applied stresses were insufficient to exceed the crushing strength of individual gravel particles, and therefore the original particle size distribution remained relatively stable. The increases in Maximum Dry Density (MDD) and California Bearing Ratio (CBR) observed at these energy levels can therefore be attributed primarily to improved particle interlocking and more efficient packing of the granular structure (Das, 2010; Chen et al., 2018).

As compaction energy increased, however, the stresses transmitted through particle contacts became sufficiently large to cause particle fracture and abrasion, producing additional fine particles. This behaviour is consistent with the concept of particle breakage in granular soils, where high contact stresses between particles lead to crushing and modification of the soil fabric (Hardin, 1985). The effect was particularly evident for the larger rammer masses and higher numbers of blows, which generated greater impact forces and higher cumulative compaction energies.

Moderate particle breakage may contribute to improved densification by filling void spaces between coarse particles. However, excessive particle breakage can negatively affect the mechanical performance of granular materials by disrupting the coarse particle skeleton that provides the primary load-bearing framework. The resulting increase in fines content may reduce inter-particle friction and increase compressibility, which can ultimately reduce strength parameters such as CBR (Zhang & Buscarnera, 2015; Youventharan et al., 2021).

Overall, the results indicate that particle breakage increases with compaction energy and plays an important role in controlling the engineering behavior of gravel materials. While limited breakage may enhance packing efficiency, excessive particle crushing can significantly modify the grain size distribution and reduce the structural stability of the granular matrix. These observations further highlight the importance of identifying an optimal compaction energy range that maximizes density and strength while minimizing undesirable particle degradation.

3.6 Integrated Energy Threshold Behavior

By correlating compaction energy (Table 1) with MDD, OMC, CBR, and fines content, three distinct behavioral zones were identified. At low energies (< 1,000 kJ/m³), incomplete densification resulted in lower MDD and CBR values. Intermediate energy levels (≈ 2,500–3,500 kJ/m³) produced maximum MDD and CBR, with controlled particle breakage, corresponding closely to Modified Proctor energy (BS 1377, 1990). At high energies (> 4,000–5,000 kJ/m³), excessive particle breakage dominated, increasing fines content and reducing both MDD and CBR. These results emphasize that compaction energy must be optimized rather than maximized to prevent structural degradation of gravel materials in pavement construction. Figure 7 is relative breakage ratio showing variation of fines with increasing compaction energy.

The relationship between relative breakage ratio and compaction energy indicates that particle breakage increases progressively with increasing compaction energy for all rammer weights. At lower compaction energies, only minor increases in fines were observed, suggesting limited particle rearrangement and minimal grain crushing. However, as the compaction energy increases, the stresses transmitted between soil particles become sufficiently high to induce particle fracture and abrasion, resulting in a significant increase in fines content. The 8.5 kg rammer produced the highest breakage ratios (up to ~234%), confirming that higher compaction energy significantly increases particle crushing. However, values did not exceed 300–400%, meaning extreme over-crushing was not reached.

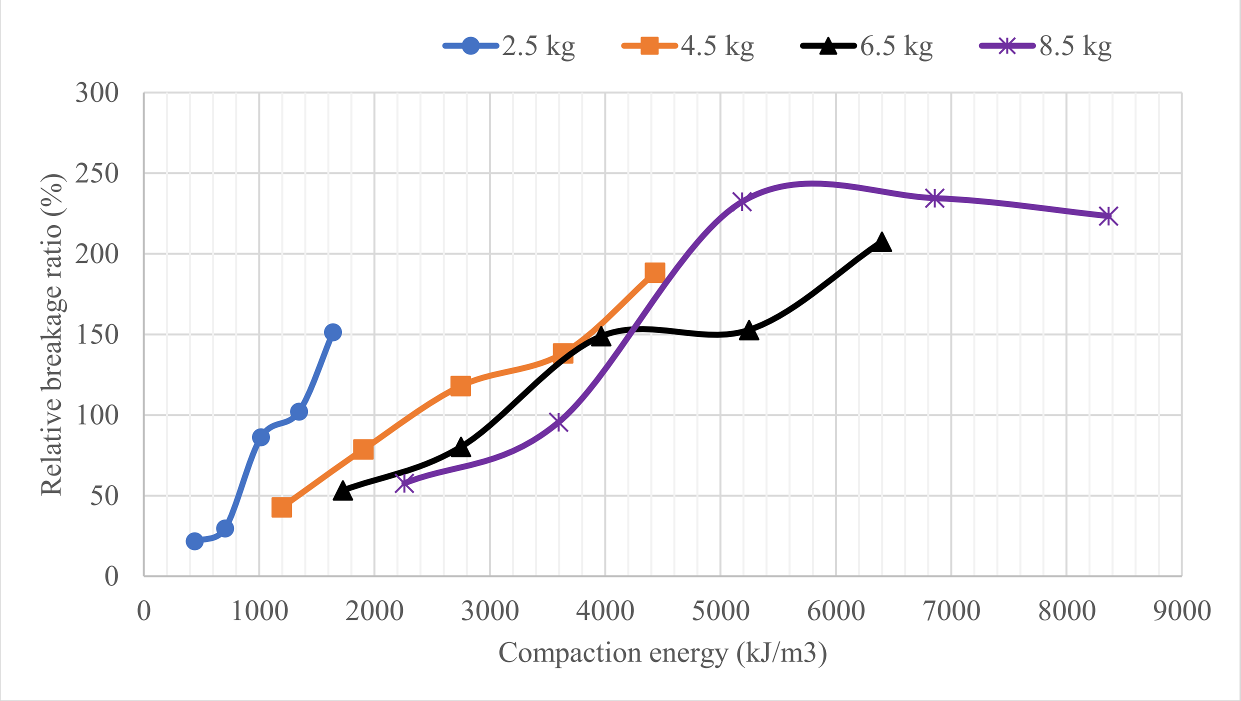

Figure 7: Relative breakage ratio vs compaction energy

The increase in breakage index with compaction energy is nonlinear. At lower energy levels, the increase in breakage is gradual, indicating that particle rearrangement dominates the compaction process. As the energy increases beyond approximately 3000–4000 kJ/m³, the rate of breakage increases significantly, suggesting a transition from particle rearrangement to particle crushing as the primary compaction mechanism. These results highlight that compaction energy strongly influences soil gradation through particle breakage. Excessive compaction energy can significantly alter the grain size distribution, potentially affecting important engineering properties such as permeability, shear strength, and compressibility. Therefore, when compacting granular materials, it is important to balance the required density with the potential for excessive particle degradation.

3.7 Regression Models (Energy – CBR – MDD)

To quantify the influence of compaction energy (CE) on the engineering properties of the gravel material, empirical regression models were developed relating CE to Maximum Dry Density (MDD) and California Bearing Ratio (CBR). The experimental results showed a non-linear relationship, where both MDD and CBR increased with increasing compaction energy up to an optimum level, after which further increases resulted in a gradual decline.

Quadratic regression models obtained using least-squares analysis provided the best fit for the observed relationships (equations 6 and 7).

$$MDD = 0.119CE - 0.000007CE^2 + 1750 \quad 6$$

$$CBR\ (\%)\} = 0.0061CE - 0.0000015CE^2 + 18 \quad 7$$

Where: CE = compaction energy (kJ/m³), MDD = maximum dry density (kg/m³), CBR = California Bearing Ratio (%)

The coefficients of determination were $R^2 \approx 0.92$ for the MDD model and $R^2 \approx 0.89$ for the CBR model, indicating strong correlations between compaction energy and the resulting material properties. The quadratic form reflects the presence of an optimal compaction energy threshold, where initial increases in energy improve densification and strength, while excessive energy promotes particle crushing and degradation (Zhang & Buscarnera, 2015).

These regression models provide a practical approach for estimating expected MDD and CBR values for different compaction energy levels. However, the equations are material-specific and depend on factors such as gradation, mineral composition, and fines content. Consequently, their application to other gravel materials should be undertaken with caution.

Conclusions

This study examined the effects of varying rammer mass and number of blows on the compaction behavior and strength characteristics of gravel materials used in pavement construction. Based on the experimental results, the following conclusions are drawn:

1. Compaction energy significantly influences density and strength characteristics. Increasing compaction energy generally improves Maximum Dry Density (MDD) and California Bearing Ratio (CBR) values up to an optimum level.
2. Existence of optimum compaction energy. For 4.5 kg and 6.5 kg rammers, the optimum performance was achieved at approximately 62 blows per layer. Beyond this level, further increases in energy resulted in reduced MDD and CBR values due to excessive particle breakage.
3. Over-compaction reduces performance. The 8.5 kg rammer produced the highest CBR (41.1%) at 27 blows per layer; however, increasing the number of blows led to progressive reductions in both density and strength. This confirms that excessive compaction energy can degrade gravel structure and diminish load-bearing capacity.
4. Optimum Moisture Content decreases with increasing compaction energy. Higher compaction energy reduced the OMC required to achieve maximum density, indicating improved packing efficiency and reduced dependence on water for particle lubrication.
5. Particle breakage alters material behavior. Increased compaction energy resulted in higher fines content and slight reductions in plasticity index. While limited breakage improved densification, excessive breakage negatively affected gradation and mechanical stability.

Overall, the results demonstrate that maximizing compaction energy does not necessarily produce superior engineering performance. Instead, identifying and applying an optimal compaction energy level is essential for ensuring durable and stable pavement layers.

Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Optimization of Compaction Energy in Field Applications. Field compaction should be carefully controlled to achieve optimal density and strength without inducing excessive particle breakage. Simply increasing compaction effort may lead to reduced material performance.

2. Monitoring of Moisture Content. Since optimum moisture content decreases with increasing compaction energy, strict control of moisture during construction is necessary to achieve the desired compaction efficiency.
3. Avoidance of Over-Compaction. The use of excessively heavy compaction equipment or excessive passes in the field should be avoided, particularly for crushable gravel materials, as it may increase fines content and reduce strength characteristics.
4. Further Research should be to quantify particle breakage using breakage indices, relate compaction energy to field compaction equipment and investigate long-term durability of over-compacted gravel under traffic loading.
5. Specification Development. Pavement design guidelines may consider specifying upper limits of compaction energy for granular base materials to prevent structural degradation during construction.

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