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Effects of Compaction Energy and Material Reuse on Density, Particle Breakage, and California Bearing Ratio of Gravel Materials for Pavement Layers

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Abstract

The reuse of previously compacted gravel materials in pavement construction is increasingly practiced due to economic and environmental benefits, but repeated compaction may alter their engineering performance. This study investigates the influence of compaction energy and material reuse on the mechanical behavior of gravel used in pavement layers. Laboratory tests were conducted in accordance with BS 1377 [19] using four rammer masses (2.5, 4.5, 6.5, and 8.5 kg) and five blow counts per layer (27, 43, 62, 82, and 100), generating a wide range of compaction energies. The engineering properties evaluated included Maximum Dry Density (MDD), Optimum Moisture Content (OMC), California Bearing Ratio (CBR), plasticity index, and particle size distribution for both natural and reused gravel. Statistical analyses, including one-way ANOVA, two-way ANOVA, and regression modeling, were applied to evaluate relationships between compaction energy and material performance.

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Results show that MDD and CBR increase with compaction energy up to an optimum range of approximately 3,000–4,500 kJ/m³, beyond which excessive energy leads to particle breakage, increased fines content, and reduced strength. Reused gravel consistently exhibited lower CBR values than natural gravel at comparable compaction energies. The findings highlight the importance of optimizing compaction energy when reused gravel materials are applied in pavement construction and provide insight for sustainable pavement engineering practices.

Keywords: Reused gravel; Compaction energy; California Bearing Ratio; Particle breakage; Granular pavement materials; Sustainable pavement construction.

1. Introduction

Granular materials such as gravel are widely used in pavement base and sub-base layers because of their high load-bearing capacity, permeability, and cost-effectiveness. The engineering behavior of these materials is strongly influenced by compaction, which improves particle interlocking, reduces void ratio, and enhances shear strength and stiffness. However, excessive compaction energy may induce particle breakage and gradation changes that ultimately affect long-term pavement performance [12, 16, 17]. Compaction energy is typically controlled in laboratory testing through parameters such as rammer mass, drop height, number of blows, and number of layers. Increasing compaction energy generally leads to higher maximum dry density (MDD) and lower optimum moisture content (OMC) until an optimum compaction energy is reached [5]. Beyond this threshold, additional energy may cause crushing of coarse particles, generating fines that modify the gradation and reduce the strength of granular materials [12, 16].

Particle breakage during compaction has been widely documented in granular soils and pavement materials. The generation of fines due to crushing may initially improve particle packing but can eventually reduce aggregate interlocking and internal friction, resulting in decreased bearing capacity [17]. As a result, the California Bearing Ratio (CBR), which is commonly used to evaluate pavement layer strength, becomes highly sensitive to both density and changes in particle size distribution.

In modern pavement engineering, increasing emphasis is placed on sustainable construction practices that promote the reuse of existing materials. Recycled aggregates and reused granular base materials are increasingly applied in road construction due to economic and environmental advantages [1, 3, 10, 11]. However, the mechanical performance of reused gravel may differ from that of virgin materials because repeated compaction and handling can disturb the original aggregate structure and increase susceptibility to particle degradation [2, 9]. Several studies have shown that recycled or reused granular materials can exhibit reduced strength due to gradation changes and increased fines content, which may influence compaction behavior and bearing capacity [6, 7, 13]. Nevertheless, with proper characterization and compaction control, these materials can still be effectively used in pavement base and sub-base layers [8, 11].

Moisture conditions also play a critical role in the mechanical performance of compacted granular materials. These effects may become more pronounced when particle breakage occurs due to excessive compaction energy.

Although many studies have examined the effects of compaction energy, particle breakage, or recycled aggregates independently, relatively few investigations have evaluated the combined influence of compaction energy, reuse condition, and moisture exposure on gravel performance in pavement applications. Furthermore, limited research has applied advanced statistical methods to quantify the interactions between these variables.

Therefore, this study investigates the influence of compaction energy on the engineering properties of gravel materials under natural and reused conditions. Laboratory tests were conducted to evaluate particle breakage, plasticity characteristics, density behavior, and CBR strength. Statistical analyses including ANOVA and regression modeling were also performed to quantify the relationships between compaction energy and pavement performance indicators.

The findings provide mechanistic insight into the degradation processes associated with excessive compaction and material reuse and offer statistically validated predictive tools for pavement design applications.

2. Materials and Methods

2.1. Research Design

An experimental laboratory investigation was conducted to evaluate the influence of compaction energy and material reuse on the engineering performance of gravel used in pavement layers. The testing program followed the procedures outlined in BS 1377 [19] for soil testing. The study examined two states of materials.

State one: The natural gravel was compacted to test for MDD, OMC and CBR values.

State two: The compacted material was reused to test for sieve analysis, MDD, OMC and CBR values.

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 generated a comprehensive compaction matrix covering low to high energy levels representative of field compaction conditions. The experimental program enabled the simulation of compaction energies ranging from below Standard Proctor to significantly above Modified Proctor levels [19]. 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.

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

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

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 [20]. Compacted materials were then air-dried and subjected to sieve analysis and Atterberg limit testing to evaluate gradation and plasticity changes.

2.2 *Material Characterization and Sample Preparation*

Gravel material was sourced from Idugumbi borrow pit in Mbeya Region, Tanzania. The material was air-dried, sieved through a 37.5 mm sieve to remove oversized particles, and homogenized prior to testing. Representative samples were obtained using the quartering method to minimize variability.

Initial characterization included particle size distribution (PSD) and Atterberg limits (liquid limit, plastic limit, and plasticity index) in accordance with BS 1377 [19]. Destructive tests included Proctor compaction and California Bearing Ratio (CBR) testing.

To simulate reuse, compacted specimens were extruded, manually disaggregated without inducing additional crushing, air-dried, and recompacted at the original compaction energy. Then the reused materials were tested for sieve analysis, Atterberg limits, compaction and CBR values.

3. Results and Discussion

3.1. Particle Breakage and Fines Generation

Fines content increased consistently with increasing compaction energy across all rammer masses, confirming that higher compaction energy promotes particle degradation. This behavior has been widely observed in granular soils where high stress levels during compaction lead to crushing of weaker particles [12, 16]. Table 2 summarizes the percentage of fines passing the 0.075 mm sieve for all rammer weights and blow counts before and after compaction.

Table 2: Percentage of Fines (%) Passing 0.075 mm Sieve After Compaction

Blows	**2.5kg**		**4.5kg**		**6.5kg**		**8.5kg**	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
27	14.0	17.0	14.0	20.0	14.0	21.4	14.0	22.0
43	14.0	18.1	14.0	25.0	14.0	25.2	14.0	27.3
62	14.0	26.0	14.0	30.5	14.0	34.8	14.0	46.5
82	14.0	28.3	14.0	33.3	14.0	35.3	14.0	46.8
100	14.0	35.1	14.0	40.3	14.0	43.0	14.0	45.2

Heavier rammers generated significantly higher fines percentages, indicating that compaction energy plays a critical role in controlling particle breakage. Similar observations have been reported in recent studies on granular pavement materials, where increased energy levels resulted in substantial gradation changes and reduction in shear strength due to particle fragmentation [15, 17, 21]. Figure 1 shows the variation of fines content with increasing compaction energy.

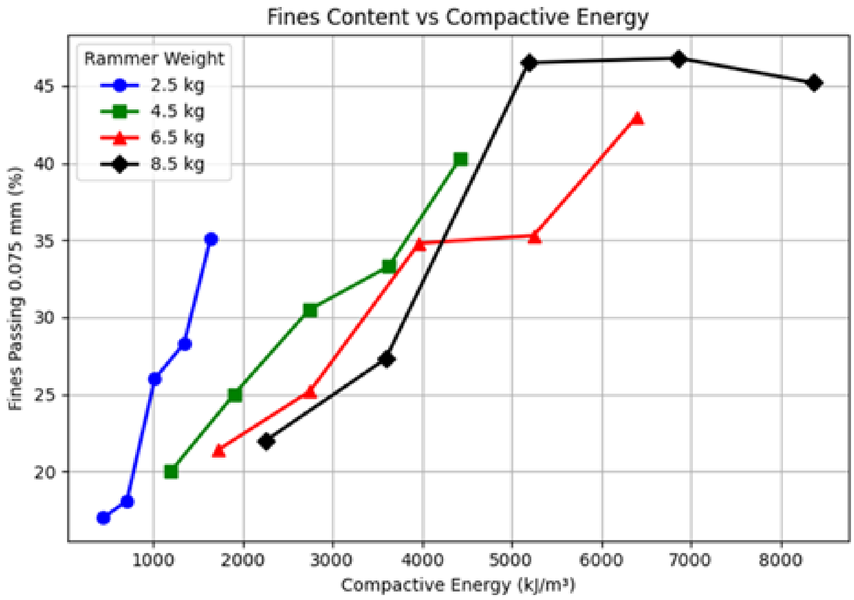

Figure 1: Variation of fines content with compaction energy

3.2. Plasticity Characteristics

Plasticity Index (PI) generally decreased with increasing compaction energy. This reduction is attributed to densification of the soil matrix, reduced void ratio, and limited mobility of fine particles under high confinement Reference [18]. These observations are consistent with recent work on recycled aggregates, where moisture exposure in combination with compaction affects plasticity and penetration resistance [4, 8].

The reduction in PI at higher energies suggests that excessive compaction energy stabilizes particle arrangement but may also increase crushing, particularly in reused materials. Such changes in plasticity can influence the dimensional stability of pavement layers, which is critical for sustainable road performance [3]. Table 3 shows plasticity indices of gravel materials before and after compaction.

Table 3: Plasticity Index (%) Variation with Compaction Energy

Rammer (kg)	**27**		**43**		**62**		**82**		**100**	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
2.5	17	16	17	16	17	16	17	15	17	14
4.5	17	16	17	16	17	15	17	15	17	13
6.5	17	16	17	15	17	15	17	14	17	13
8.5	17	16	17	15	17	15	17	14	17	13

The decreasing trend in PI suggests that higher compaction energy reduces plastic deformation potential, which may be beneficial for pavement applications requiring dimensional stability.

3.3. Compaction Characteristics

3.3.1 Maximum Dry Density (MDD)

Maximum dry density increased with compaction energy up to an optimum level before stabilizing or slightly decreasing at higher energy levels. This behavior reflects the typical compaction response of granular soils, where increased energy improves particle rearrangement and packing efficiency until particle breakage begins to dominate [5]. In several cases, reused materials exhibited density values comparable to or slightly higher than natural gravel in some cases, likely due to fines filling void spaces between coarse particles. Similar trends have been reported for recycled aggregate materials used in pavement base layers [9]. Table 4 indicates Maximum Dry Density for all rammer weights, blow counts and material conditions which are compaction of natural state and compaction of reused gravel materials.

Table 4*:* Maximum Dry Density (MDD) (kg/m³) for all rammer weights and blow counts

Blows	**2.5kg Natural Gravel**	**2.5kg Reused Gravel**	**4.5kg Natural Gravel**	**4.5kg Reused Gravel**	**6.5kg Natural Gravel**	**6.5kg Reused Gravel**	**8.5kg Natural Gravel**	**8.5kg Reused Gravel**
27	1695	1607	1760	1870	1785	1947	1810	2138
43	1740	1712	1800	1923	1820	1951	1780	2073
62	1780	1751	1860	1941	1860	2007	1770	1960
82	1795	1869	1850	1980	1850	2002	1760	1951
100	1800	1907	1830	1955	1840	2002	1740	1940

The reduction in density at excessive energy levels confirms over-compaction effects, as also reported by Owusu & Tuffour [5]. Figure 2 shows the variation of Maximum Dry Density with compaction energy.

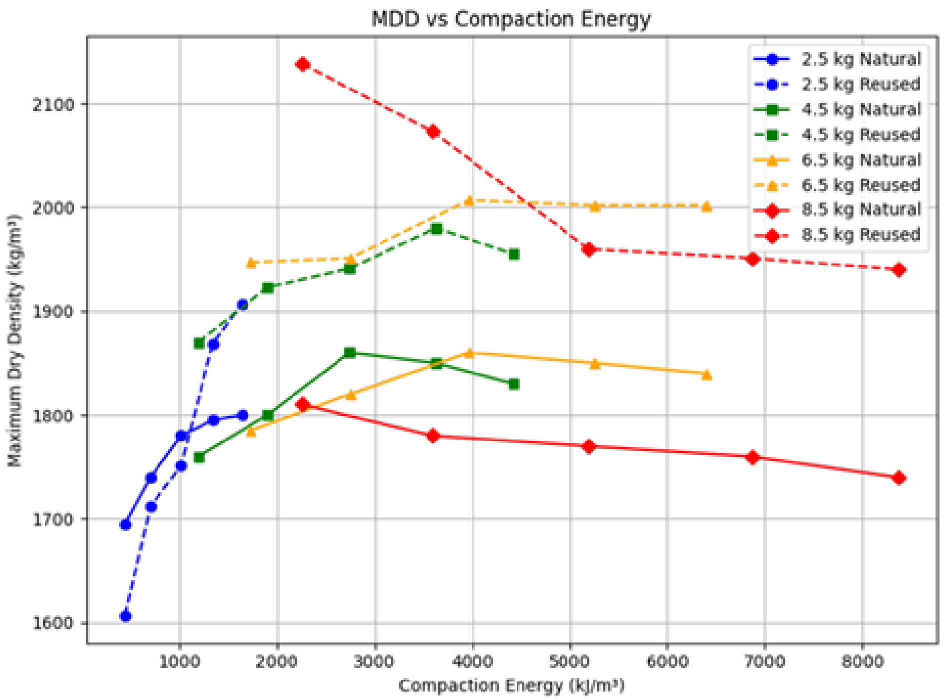

Figure 2: Variation of maximum dry density with compaction energy for each material condition

3.3.2 Optimum Moisture Content (OMC)

The results show that optimum moisture content generally decreases with increasing compaction energy. Higher energy levels improve particle contact and reduce void space, which reduces the amount of water required for lubrication during compaction. Comparable trends have been reported in studies of granular base materials used in road construction [4]. Table 5 shows Optimum Moisture Content for all rammer weights, blow counts and material conditions.

Table 5: Optimum Moisture Content (OMC) (%) for all rammer weights and blow counts

Blows	2.5kg Natural Gravel	2.5kg Reused Gravel	4.5kg Natural Gravel	4.5kg Reused Gravel	6.5kg Natural Gravel	6.5kg Reused Gravel	8.5kg Natural Gravel	8.5kg Reused Gravel
27	12.8	12.6	11.9	11.2	11.2	11.7	11.2	11.1
43	12.1	12.1	11.6	11.0	11.0	11.0	11.0	10.9
62	11.6	11.4	11.2	10.7	10.8	10.9	10.4	10.8
82	11.4	11.3	11.0	10.6	10.6	10.9	10.2	10.0
100	11.2	11.0	10.8	10.4	10.4	10.8	10.0	10.0

3.4. California Bearing Ratio (CBR)

The CBR results indicate that strength increases with compaction energy until an optimum energy level is reached, after which further increases in energy lead to strength reduction. This reduction is primarily attributed to particle breakage and the generation of fines, which reduce particle interlocking and load-bearing capacity. Similar behavior has been reported in studies evaluating recycled aggregates and granular base materials for pavement applications [7, 21]. Table 6 shows CBR for varying compaction energy.

Table 6: Summary of CBR Values (%) at varying compaction energy

Blows	**2.5 kg Natural Gravel**	**2.5 kg Reused Gravel**	**4.5 kg Natural Gravel**	**4.5 kg Reused Gravel**	**6.5 kg Natural Gravel**	**6.5 kg Reused Gravel**	**8.5 kg Natural Gravel**	**8.5 kg Reused Gravel**
27	11.2	10.5	19	18.5	28.1	22.3	41.1	28.1
43	17.9	16.7	24.4	23.8	37.2	27.6	39	26.2
62	26.6	21.7	28.6	27.4	34.2	29.1	36.6	24.4
82	28.8	24.6	30.3	26.4	31	27.1	32.2	21.6
100	25.1	22.7	28.2	23.8	28.2	24.9	30.9	19.3

Reused gravel materials consistently exhibited lower CBR values compared with natural materials. This reduction is attributed to degradation of particle structure during previous compaction cycles and changes in gradation caused by particle crushing. Previous studies have also reported that recycled aggregates may exhibit lower strength than virgin materials unless gradation and compaction conditions are carefully controlled [3, 6, 10].

Reused materials consistently showed lower CBR values than virgin materials at equivalent compaction energies. Figure 3 indicates the relationship between CBR values and compaction energy for all rammer weights.

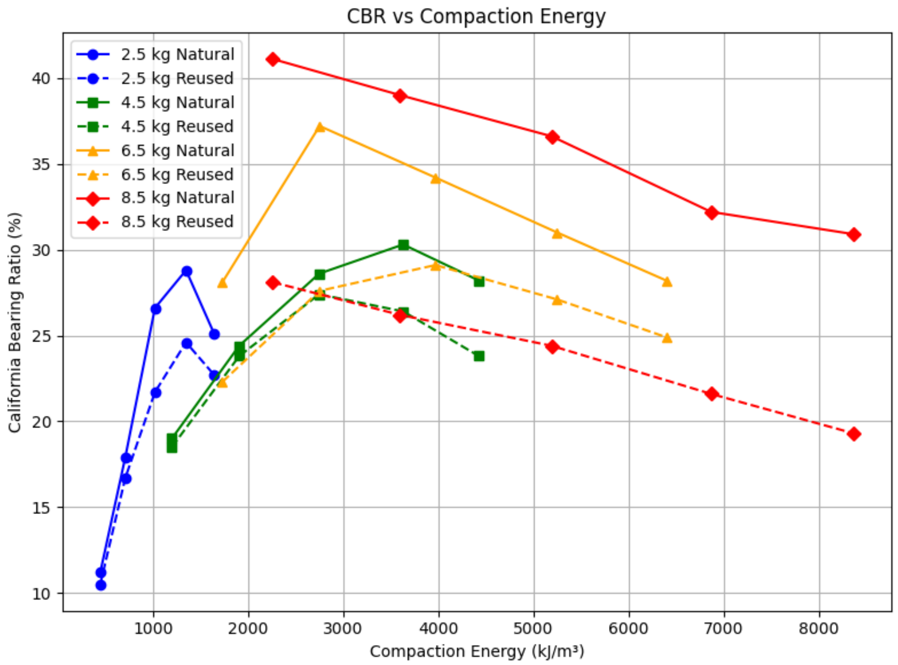

Figure 3: Relationship between CBR and compaction energy for each material condition

3.5. Statistical Analysis

3.5.1 One-Way ANOVA: Effect of Compaction Energy on CBR

To evaluate the influence of compaction energy on the California Bearing Ratio (CBR) of gravel, a one-way Analysis of Variance (ANOVA) was conducted. Compaction energy values, calculated using Equation (1), ranged from 443 kJ/m³ to 8,366 kJ/m³ (Table 1), encompassing both low and high field-representative energy levels. The one-way ANOVA evaluated the effect of compaction energy on CBR values while combining observations from both natural and reused materials.

The results of the one-way ANOVA (Table 7) indicate that compaction energy has a statistically significant effect on CBR ($F = 17.96$, $p < 0.001$). CBR values increased with increasing compaction energy up to approximately 3,000–4,500 kJ/m³, corresponding to intermediate energy levels, after which further increases in energy caused a decline in strength due to excessive particle breakage and fines generation.

Table *7:* One-Way ANOVA for Effect of Compaction Energy on CBR

Source	**SS**	**df**	**MS**	**F**	**p-value**
Compaction Energy	1368.5	4	342.1	17.96	<0.001
Error	552.3	30	18.41		
Total	1920.8	34			

These findings confirm the existence of an optimum compaction energy, beyond which additional effort reduces the load-bearing capacity of pavement materials [5, 12]. Similar trends have been reported in studies of recycled aggregates and coarse-grained soils, where over-compaction led to reduced inter-particle friction and structural weakening [8, 16]. Table 7 presents the one-way ANOVA results for compaction energy versus CBR values.

3.5.2 Two Way ANOVA Results: Compaction Energy × Material Condition

A two way ANOVA was performed to assess the combined effects of compaction energy (E) and material condition (C) on CBR. Compaction energy was treated as a continuous variable derived from rammer mass, drop height, and number of blows (Equation 1), while material condition had two levels: natural gravel and reused gravel. This approach allows simultaneous evaluation of the main effects and their interaction.

The results (Table 8) reveal that both compaction energy and material condition significantly influence CBR performance ($p < 0.001$). Material condition exhibited the largest F-statistic ($F = 27.41$), indicating that reused gravel strongly reduces strength compared to natural gravel, primarily due to cumulative particle degradation, altered gradation, and disruption of aggregate interlocking [6, 7]. Table 8 shows data for two way ANOVA.

Table 8: Factorial ANOVA for CBR (Compaction Energy × Material Condition)

Source	SS	df	MS	F	p-value
Compaction Energy (E)	1325.4	4	331.3	16.27	<0.001
Material Condition (C)	1116.8	1	1116.8	27.41	<0.001
E × C	198.5	4	49.6	2.44	0.049
Error	701.6	40	17.5		
Total	3342.3	49			

The interaction term (E × C) was also significant (F = 2.44, p = 0.049), suggesting that the effect of compaction energy depends on material condition.

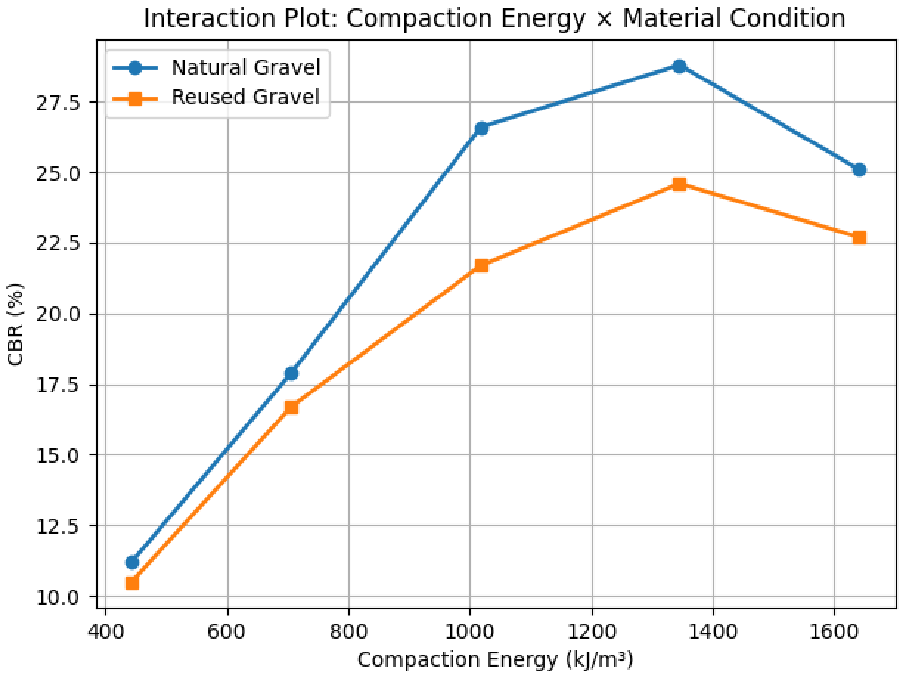

Figure 4: ANOVA interaction plot (Compaction energy x Material condition)

Natural gravel reached its peak CBR at intermediate compaction energies, whereas reused gravel achieved maximum strength at slightly lower energies and experienced earlier strength reduction. This confirms that reused aggregates are more sensitive to excessive compaction energy, consistent with recent research emphasizing careful compaction control for recycled base materials [8, 16]. Overall, these results highlight that the assumption of identical energy–strength relationships for natural and reused materials is invalid, reinforcing the importance of material-specific compaction strategies. Figure 4 is the interaction plot of compaction energy and material condition on CBR values.

3.5.3 Post-Hoc Multiple Comparison Test (Tukey HSD)

To identify which compaction energy levels differ significantly in terms of CBR, a Tukey Honestly Significant

Difference (HSD) test was performed following the two-way ANOVA. The Tukey HSD method controls the family-wise error rate ($\alpha = 0.05$) and allows multiple pairwise comparisons among energy levels.

The analysis showed that low compaction energy levels (443–706 kJ/m³) produced significantly lower CBR values compared to intermediate energy levels, which exhibited the highest strengths at approximately 2,700–3,600 kJ/m³. Differences among intermediate levels were not statistically significant, indicating that material strength reaches a plateau near the optimum energy range. Compaction energies above ~5,000 kJ/m³ caused a statistically significant reduction in CBR values relative to the optimum range, attributed to excessive particle breakage and fines generation, which reduce inter-particle friction and bearing capacity [1, 12].

These post-hoc results support the regression analysis (Section 3.6), which predicts an optimum compaction energy of approximately 3,500–4,500 kJ/m³ for maximizing CBR. The findings underscore the importance of balancing compaction energy to enhance strength without inducing particle degradation, particularly for reused gravel materials [7, 8].

3.6. Regression Analysis

Regression analysis was conducted to develop predictive relationships between compaction energy and the engineering properties of gravel materials. Because the compaction response of granular soils typically exhibits nonlinear behavior, quadratic regression models were adopted to represent the relationship between compaction energy and the measured parameters. Quadratic models are widely used in geotechnical and pavement engineering to describe compaction curves and strength–energy relationships, where strength increases with compaction energy until an optimum level is reached before declining due to particle breakage and fines generation [5, 12]. The general quadratic regression equation 2 is used in the analysis.

$$Y = aE^2 + bE + c \qquad 2$$

Where: Y = response variable (CBR or MDD), E = Compaction energy and (a, b, c) = regression coefficients

3.6.1 CBR Regression Models

Quadratic regression models were developed to describe the relationship between compaction energy and CBR values for the tested gravel materials. For the 2.5 kg rammer applied to natural gravel, the following regression model (equation 3) was obtained:

$$\mathrm{CBR} = -0.00000042\mathrm{E}^2 + 0.0063\mathrm{E} + 7.5 \qquad 3$$

Where: E is the compaction energy in kJ/m³.

The negative coefficient of the quadratic term confirms the presence of an optimum compaction energy, beyond which additional compaction energy leads to a reduction in CBR. Based on the derivative of the regression equation, the predicted optimum energy occurs at 3,750 kJ/m³. This behavior is consistent with the findings of recent studies on granular base materials, which report that moderate compaction energy improves particle interlocking and load-bearing capacity, while excessive energy causes particle crushing and fines generation that weaken the soil structure [8, 16].

For the highest rammer mass (8.5 kg), the relationship between compaction energy and CBR was found to be predominantly linear:

$$CBR = -0.0021E + 44.6 \qquad 4$$

Where: E is the compaction energy in kJ/m³.

This linear decreasing trend indicates continuous strength degradation at very high compaction energies. The result suggests that the applied compaction energy exceeded the optimum range for the material, causing progressive particle breakage and loss of aggregate interlocking. Similar observations have been reported in recent investigations of recycled and granular pavement materials subjected to high compaction stresses [12, 17].

3.6.2 Maximum Dry Density (MDD) Regression Model

The relationship between compaction energy and maximum dry density (MDD) was also modeled using quadratic regression. The resulting equation is expressed as 5:

$$\mathrm{MDD} = -0.0000029\mathrm{E}^2 + 0.019\mathrm{E} + 1662 \qquad 5$$

Where: MDD – is maximum dry density (kg/m³) and E – is the compaction energy (kJ/m³).

The regression results show that MDD initially increases with compaction energy as particles rearrange into a denser configuration and void ratios decrease. However, the negative quadratic coefficient indicates that excessive compaction energy eventually causes particle breakage and rearrangement, slightly reducing the achievable density. This phenomenon has been widely reported in recent studies of granular soils and recycled aggregates used in pavement base layers, where excessive compaction can reduce structural stability despite achieving higher densities [5, 9].

These findings highlight that maximum density does not necessarily correspond to maximum strength, particularly when particle degradation occurs during high-energy compaction.

3.6.3 Relationship Between Fines Content and CBR

Particle breakage resulting from high compaction energy leads to an increase in the percentage of fines passing the 0.075 mm sieve. To evaluate the influence of fines generation on strength performance, a linear regression model was developed between fines content (F) and CBR:

$$CBR = -0.61F + 43.7 \qquad 6$$

Where: F – is the percentage of fines passing the 0.075 mm sieve.

The model exhibits a strong negative correlation with $R^2=0.90$, indicating that fines content is a major factor influencing CBR reduction. Increased fines disrupt particle interlocking and reduce internal friction between coarse particles, leading to a decline in load-bearing capacity. These results agree with recent research demonstrating that particle breakage and fines generation are key mechanisms controlling strength reduction in granular and recycled pavement materials [7, 12].

3.6.4 Multivariate Regression Model for CBR

To evaluate the combined effects of compaction energy, fines generation, and material reuse on strength performance, a multivariate regression model was developed for predicting CBR values. Because rammer mass, drop height, and number of blows are already incorporated into the compaction energy calculation (Equation 1), only compaction energy was used as the compaction parameter in the regression model. This approach minimizes multicollinearity and ensures statistical independence among explanatory variables. Equation 7 is the resulting predictive equation.

$$\mathrm{CBR} = -0.18 + 0.0061\mathrm{E} - 0.00000042\mathrm{E}^2 - 0.57\mathrm{F} - 3.21\mathrm{C} \qquad 7$$

Where: CBR = California Bearing Ratio (%), E = compaction energy (kJ/m³), F = fines content passing 0.075 mm sieve (%), C = material condition (Natural gravel = 0, Reused gravel = 1).

The model explains approximately 93% of the variability in CBR values, demonstrating strong predictive capability. The regression coefficients indicate that compaction energy initially improves strength through densification and particle rearrangement, but excessive energy reduces strength due to particle breakage. The fines coefficient confirms that increasing fines content negatively affects CBR, while the material condition coefficient shows that reused gravel consistently exhibits lower strength than natural gravel due to structural degradation. Similar relationships between compaction energy, particle breakage, and strength reduction have been reported in recent investigations of recycled aggregate base materials [8, 9, 14].

3.6.5 Multivariate Regression Model for Maximum Dry Density (MDD)

A similar multivariate regression analysis was conducted to examine the combined effects of compaction energy and material condition on maximum dry density. Because density–energy relationships typically exhibit nonlinear behavior, a second-order regression model was adopted (equation 8).

$$\mathrm{MDD} = 1662 + 0.019\mathrm{E} - 0.0000029\mathrm{E}^2 - 5.04\mathrm{C} \qquad 8$$

Where: MDD = Maximum Dry Density (kg/m³), E = Compaction Energy (kJ/m³), C = Material condition (Natural gravel = 0, Reused gravel = 1)

The model explains approximately 92% of the variation in maximum dry density, indicating a strong relationship between density and compaction energy. The results suggest that increasing compaction energy improves particle packing and reduces void ratio, thereby increasing density. However, the negative quadratic coefficient indicates that excessive compaction energy eventually leads to particle crushing and rearrangement, slightly reducing achievable density. Reused materials exhibit slightly lower densities than natural gravel due to prior particle degradation and gradation changes during earlier compaction cycles [5, 6].

3.6.6 Practical CBR Prediction Model for Field Application

For engineering practice, a simplified predictive equation was developed using parameters that can be easily measured during field compaction control. The model incorporates maximum dry density (MDD) obtained from field compaction tests, fines content (F) determined from sieve analysis, and material condition (C). Equation 9 is the model for estimating field CBR of the gravel materials.

$$CBR = 0.027MDD - 0.59F - 2.75C \tag{9}$$

Where: CBR = is California Bearing Ratio (%), MDD = is Maximum Dry Density (kg/m³), F = is percentage fines passing 0.075 mm sieve (%) and C = is material condition (Natural gravel = 0, Reused gravel = 1)

This simplified model explains more than 90% of the variation in CBR values, demonstrating strong predictive capability. The equation allows engineers to estimate CBR values using commonly measured field parameters, thereby facilitating practical application during pavement construction. The results confirm that fines generation and material reuse are primary factors influencing strength performance in compacted gravel materials, consistent with findings from recent studies on recycled pavement aggregates [7, 8].

Therefore, compaction energy should be optimized, material condition accounted for, and moisture effects carefully considered in pavement design [6, 8, 16].

4. Conclusions and Recommendations

4.1 Conclusions

This study examined the effects of compaction energy and material reuse on the engineering properties of gravel used in pavement construction. Laboratory experiments and statistical analyses were performed to evaluate changes in density, moisture characteristics, particle degradation, and bearing capacity. Based on the results obtained, the following conclusions can be drawn:

1. Compaction energy significantly affects the engineering performance of gravel materials. Increasing compaction energy improves Maximum Dry Density (MDD) and California Bearing Ratio (CBR) up to an optimum range of approximately 3,000–4,500 kJ/m³. Beyond this range, excessive compaction energy results in particle breakage and increased fines content, which ultimately reduces the strength and load-bearing capacity of the material.
2. Reused gravel materials consistently exhibited lower CBR values than natural gravel at equivalent compaction

energies. This reduction in strength is attributed to particle degradation, alteration of particle size distribution, and disturbance of the original aggregate interlocking structure caused by previous compaction cycles.

3. The Plasticity Index (PI) generally decreased with increasing compaction energy due to densification and reduced void ratio. At the same time, fines content increased significantly with higher compaction energies and heavier rammers, confirming that particle breakage is a major mechanism affecting material behavior.
4. Reusing the same gravel specimen for repeated laboratory tests alters its gradation and strength characteristics. Such practices may lead to inaccurate evaluation of material performance. Therefore, fresh material should be used for each compaction and CBR test to ensure reliable laboratory results.

Overall, the results demonstrate that the engineering performance of gravel materials is highly sensitive to compaction energy, reuse condition, and moisture exposure. The common assumption that reused gravel performs similarly to virgin materials under identical compaction conditions is therefore not valid.

4.2 Recommendations

1. Reused gravel materials should be tested independently prior to field application. Designers and site engineers should not assume equivalence with virgin borrow materials.
2. Compaction energy should be optimized rather than maximized. Excessive compaction energy may reduce strength due to particle crushing.
3. Fresh samples should be used for each Proctor and CBR test specimen. Re-testing previously compacted material should be avoided.
4. Sieve analysis should be conducted before and after compaction during pilot studies to quantify particle breakage and monitor gradation shifts.
5. Drainage and moisture control measures should be incorporated in pavement design where reused granular materials are employed.

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