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Effects of Rammer Weight and Number of Blows on the Engineering Properties of Gravel Materials for Road Construction

Effects of Rammer Weight and Number of Blows on the Engineering Properties of Gravel Materials for Road Construction

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Abstract
This study examined how increasing laboratory compaction energy by varying the rammer weight and the number of blows per layer affects the engineering properties of gravel used in road construction. A clayey gravel (AASHTO A-2-6) from Idugumbi borrow pit, Mbeya, Tanzania, was compacted in a standard CBR mould in five layers using 2.5, 4.5, 6.5 and 8.5 kg rammers with 27, 43, 62, 82 and 100 blows per layer, giving compaction energies of 0.44–8.36 MJ/m³ (0.16–3.05 times BS heavy compaction). Because the 2.5 kg rammer was dropped from 300 mm and the others from 450 mm, the results were also analysed in terms of energy per unit volume and energy per blow. For each energy level, the Atterberg limits, moisture–density relationship and California Bearing Ratio (CBR) were determined following BS 1377 and the Tanzanian Ministry of Works laboratory manual; CBR was taken as the higher of the 2.5 mm and 5.0 mm values, and triplicate CBR results were analysed by two-way analysis of variance. Maximum dry density (MDD) and CBR did not respond to compaction energy in the same way, and total energy alone did not explain the results. The highest MDD (1860–1868 kg/m³) was obtained at 62 blows with the 4.5 kg and 6.5 kg rammers (2.7–4.0 MJ/m³), whereas the highest CBR (45.8% and 45.5%) was obtained with the 8.5 kg rammer at 27 blows and the 6.5 kg rammer at 43 blows (2.3–2.8 MJ/m³), that is, under different compaction conditions and at lower energy than the density peak. The number of blows at which CBR peaked fell as rammer weight increased, and rammer weight, number of blows and their interaction all had significant effects on CBR ($p < 0.001$). Beyond its peak, MDD declined for the 4.5, 6.5 and 8.5 kg rammers and CBR declined for all rammers except the 2.5 kg rammer, which was attributed to particle crushing and the generation of fines. Optimum moisture content and plasticity index decreased as the number of blows increased. The results are based on one borrow pit material tested in the laboratory; field compaction and other gravel types were not examined. Compaction energy for gravel layers should be optimised rather than maximised and field compaction energy and moisture content should be monitored to avoid over-compaction and particle degradation.

Introduction

Gravel materials consist of a mixture of course- and fine-grained particles and have physical and mechanical properties that make them useful for road construction (Chen et al., 2018). Their wide availability, cost-effectiveness and good load-bearing capacity have led to their use in many infrastructure projects worldwide (Lillian et al., 2025). Gravel soils, which are typically excavated from borrow pits and transported to construction sites, play a critical role in the construction of embankments, improved subgrade, and the subbase and base layers of flexible pavements (Awed et al., 2020).

The effective use of gravel in pavement layers depends largely on achieving optimum compaction (BS 1377, 1990). Compaction improves the strength, stiffness, particle interlocking and stability of soil by reducing air voids and increasing packing density, thereby enhancing its performance and durability under traffic loading (Das, 2010). Compaction energy is the energy applied to the material through mechanical means, and its effectiveness depends on the moisture content at which the material is compacted (BS 1377, 1990).

Standard laboratory compaction methods date back to the work of Ralph R. Proctor, who introduced the Standard Proctor test in 1933. The test uses a 2.5 kg rammer dropped from a height of 300 mm to compact soil in three layers, each receiving 27 blows, in a mould of 996 cm^3 (BS 1377, 1990; Das, 2010). As traffic loads increased and construction technology and service conditions changed, the Standard Proctor test proved inadequate for some materials and applications. The Modified Proctor test was therefore introduced in the 1950s; it uses a heavier 4.5 kg rammer, a drop height of 450 mm, five layers and a mould of 2243 cm^3 to apply greater compaction energy (BS 1377, 1990).

Further research and field experience showed that even the Modified Proctor energy could be insufficient for compacting coarse granular materials in certain applications and environments. Alternative procedures were therefore developed, such as the Tex-113-E method of the Texas Department of Transportation, which applies 100 blows per layer with a 4.55 kg rammer to achieve more effective densification of base materials (Tex-113-E, 2011). The European standard EN 13286-2 (2010) also provides a higher-energy method in which a 15 kg rammer is dropped from 600 mm to represent more intensive compaction of coarse gravel materials.

Each of these methods reflects a trend towards greater compaction energy aimed at improving the properties of granular materials. However, limited information is available on how compaction energy beyond the standard and modified Proctor levels affects the engineering properties of gravel used for road construction. These properties, which include particle size distribution, Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC) and California Bearing Ratio (CBR), are central to pavement design and performance. The aim of this study was therefore to investigate the effect of increasing laboratory compaction energy, achieved by varying the rammer weight and the number of blows per layer, on the Atterberg limits, fines content, MDD, OMC and CBR of a gravel material used in road construction.

Part of the experimental data set (the MDD, OMC and CBR results for the 20 combinations) was presented in preliminary form by Makindi et al. (2026). The present paper extends that work by expressing all results in terms of compaction energy per unit volume and energy per blow, recalculating CBR in accordance with BS 1377-4 (1990), analysing the replicate CBR results statistically, evaluating the material against the Tanzanian specification for natural gravel sub-base, and examining why maximum density and maximum bearing capacity occur under different compaction conditions.

Method

The study adopted an experimental, laboratory-based design in which a single gravel material was compacted at different energy levels by varying the rammer weight and the number of blows per layer, while the number of layers and the mould size were kept constant. The engineering properties obtained at each energy level were then compared to determine the effect of increasing compaction energy. Because the 2.5 kg rammer was dropped from 300 mm whereas the heavier rammers were dropped from 450 mm, the energy delivered per blow differed through both rammer mass and drop height; the results were therefore analysed in terms of energy per blow and total energy per unit volume, as well as rammer weight and number of blows. All tests were performed in accordance with BS 1377 (1990) and the Ministry of Works laboratory testing manual (MoW, 2000).

Materials

The gravel was sourced from the Idugumbi borrow pit in Mbeya Region, Tanzania, where samples were excavated at a depth of 2 to 3 m. The samples were transported to the Civil Engineering Materials Testing Laboratory of Mbeya University of Science and Technology, where they were air-dried before testing (Figure 1A).

Compaction energy programme

Compaction energy was varied through the weight of the rammer and the number of blows applied to each layer. Four rammers were used (Figure 2A): a 2.5 kg rammer with a drop height of 300 mm, and 4.5 kg, 6.5 kg and 8.5 kg rammers, each with a drop height of 450 mm. For each rammer, the material was compacted in a standard CBR mould in five layers using 27, 43, 62, 82 and 100 blows per layer, giving 20 combinations of rammer weight and number of blows (Table 1). The combination of the 4.5 kg rammer and 62 blows per layer corresponds to the BS heavy compaction energy used to characterise the original material.

The 2.5 kg rammer was used with its fixed standard drop of 300 mm (the BS 1377 light-compaction rammer), so that the lowest-energy series remained tied to the standard light-compaction equipment, while the 4.5 kg BS heavy rammer and the two heavier rammers were all dropped from 450 mm. Rammer mass and drop height are therefore confounded for the 2.5 kg series only: differences between this rammer and the others reflect a difference in energy per blow (7.4 J against 19.9–37.5 J) rather than in mass alone, whereas the 4.5, 6.5 and 8.5 kg series differ only in rammer mass.

The compaction energy applied per unit volume of soil for each combination can be expressed as

$$E = (W \times h \times N \times n) \,/\, V$$

where W is the weight of the rammer ($W = m \cdot g$, where m is the rammer mass in kg and g = 9.81 m/s²), h is the drop height (m), N is the number of blows per layer, n is the number of layers and V is the volume of the mould (m³), so that E is obtained in J/m³. Because n and V were constant in this study, the energy increased in direct proportion to the number of blows for a given rammer and in proportion to the product of rammer weight and drop height for a given number of blows.

With n = 5 and V = 2243 cm³ (mould of 150 mm diameter and 127 mm height), the energy per blow was 7.4 J for the 2.5 kg rammer and 19.9, 28.7 and 37.5 J for the 4.5, 6.5 and 8.5 kg rammers. The resulting energies for the 20 combinations, given in Table 2, range from 443 kJ/m³ (2.5 kg, 27 blows) to 8364 kJ/m³ (8.5 kg, 100 blows), that is, from 0.16 to 3.05 times the BS heavy energy (4.5 kg, 62 blows, 2745 kJ/m³). For comparison, BS light-compaction in the CBR mould (2.5 kg rammer, 300 mm drop, three layers of 62 blows) corresponds to about 610 kJ/m³. Because rammer weight and number of blows were combined factorially, several combinations deliver similar total energy with different energy per blow; for example, the 4.5 kg rammer at 62 blows and the 6.5 kg rammer

at 43 blows both apply about 2.75 MJ/m³. This allows the effect of energy per blow to be compared at similar total energy.

Laboratory tests

Characterisation of the original material

The original material was characterised by sieve analysis (Figure 3A(i)), Atterberg limits (liquid limit, plastic limit, plasticity index and linear shrinkage) and classification according to the AASHTO system (AASHTO, 1986). The moisture–density relationship was determined by BS heavy compaction to obtain the MDD and OMC (Figure 3A (ii)). A three-point CBR test was then carried out to determine the CBR at 95% of MDD (Figure 3A(iii)) (BS 1377, 1990; MoW, 2000). For this test, specimens were mixed and compacted at OMC using (i) a 4.5 kg rammer with 62 blows per layer in five layers, (ii) a 4.5 kg rammer with 30 blows per layer in five layers and (iii) a 2.5 kg rammer with 62 blows per layer in three layers, and were soaked in water for four days before penetration.

Tests at varying compaction energy

For the moisture–density relationship, portions of the air-dried material were mixed with increasing amounts of water and compacted in the mould using the selected rammer and number of blows. The bulk density and moisture content of each compacted specimen were measured, the dry density was calculated, and the MDD and OMC were taken from the peak of the dry density–moisture content curve.

For each combination of rammer weight and number of blows, the moisture–density relationship was determined to obtain the MDD and OMC, and a single-point CBR test was carried out. The CBR was calculated as the ratio, expressed as a percentage, of the force required to drive the plunger to a given penetration to the standard force for the same penetration (13.2 kN at 2.5 mm and 20.0 kN at 5.0 mm). In accordance with BS 1377-4 (1990), Clause 7, the CBR was calculated at both 2.5 mm and 5.0 mm penetration and the higher value was adopted as the CBR. The original submission reported the mean of the two values; all CBR values in this paper have therefore been recalculated from the penetration curves (Figure 5A). The value at 5.0 mm was the higher in all 20 combinations. Three specimens were tested for each combination. After testing, the compacted material was air-dried and tested for particle size distribution and Atterberg limits to determine how compaction energy had changed its gradation and plasticity.

Data analysis

The results at each energy level were compared with those at the other energy levels and with the properties of the original material. Trends in MDD, OMC, CBR and plasticity with rammer weight and number of blows were examined graphically and, using the calculated energies, against compaction energy per unit volume. The triplicate CBR results were analysed by two-way analysis of variance (ANOVA) with rammer weight and number of blows as fixed factors and their interaction included, and by least-squares regression of CBR on the natural logarithm of energy per unit volume, with and without rammer weight as a second predictor (significance level 0.05). Because the laboratory replicate records hold the CBR index as originally calculated (the mean of the 2.5 mm and 5.0 mm values), the statistical analysis was carried out on these values; their ranking across the 20 combinations agreed closely with that of the BS values (Spearman $\rho = 0.93$). MDD and OMC were determined once for each combination and were not analysed statistically; their repeatability was judged from the triplicate BS heavy compaction tests on the original material.

Results

Properties of the original gravel

The gravel was reddish-brown and was classified as A-2-6 (clayey gravel) under the AASHTO system (Figure 3A). It contained 11% fines (passing the 0.075 mm sieve), 28% sand (passing the 2.00 mm sieve and retained on the 0.075 mm sieve) and 61% gravel (passing the 28 mm sieve and retained on the 2.00 mm sieve). The liquid limit (LL), plastic limit (PL), plasticity index (PI) and linear shrinkage were 34%, 17%, 17% and 7%, respectively. The PI of 17% indicates that the fines have medium plasticity (Das, 2010) and exceeds the maximum PI of 12% specified for natural gravel sub-base material of class G25 in the Tanzanian Pavement and Materials Design Manual (MoW, 1999, Table 7.3). BS heavy compaction gave an MDD of 1860 kg/m^3 at an OMC of 10.5%, and the three-point test gave a soaked CBR of 21% at 95% of MDD.

The AASHTO classification describes the soil but does not by itself establish whether it is acceptable for a particular pavement layer. The material was therefore evaluated against the Tanzanian requirements for natural gravel sub-base (class G25), the layer for which gravels of this type are normally used. Under those requirements the untreated gravel did not qualify as G25: besides its PI exceeding the limit, its soaked CBR of 21% at 95% of BS heavy MDD is below the G25 minimum of 25% (MoW, 1999), so it would be limited to a lower material class, such as G15 for improved subgrade, subject to that class's other requirements.

Atterberg limits

Table 1 summarises the Atterberg limits of the gravel after compaction at each rammer weight and number of blows. For every rammer, the LL and PI decreased gradually as the number of blows increased; the PI fell from 16% at 27 blows to 13–14% at 100 blows. At a given number of blows, changing the rammer weight had little effect on the PI. Sieve analysis of the compacted samples showed that the fines content increased with compaction energy; with the 8.5 kg rammer, fines increased from 22% at 27 blows to 50% at 100 blows. With 50% passing the 0.075 mm sieve, the material no longer meets the A-2 limit of 35%, so heavy compaction changed its AASHTO classification group.

Table 1: Atterberg limits of the gravel after compaction at different rammer weights and numbers of blows

Number of blows	2.5 kg rammer			4.5 kg rammer			6.5 kg rammer			8.5 kg rammer		
	LL	PL	PI	LL	PL	PI	LL	PL	PI	LL	PL	PI
27	34	18	16	34	16	16	33	17	16	33	17	16
43	33	17	16	32	16	16	32	17	15	32	17	15
62	32	16	16	32	15	15	32	17	15	31	16	15
82	31	16	15	31	15	15	30	16	14	30	16	14
100	30	16	14	30	13	13	29	16	13	30	16	13

Note. LL = liquid limit; PL = plastic limit; PI = plasticity index. All values are in percent.

Table 2 summarises the compaction energy, MDD, OMC and CBR for all 20 combinations; these values are used in the sections that follow.

Table 2: Compaction energy, maximum dry density, optimum moisture content and CBR for each combination of rammer weight and number of blows

Rammer (kg)	Blows per layer	Energy per blow (J)	E (kJ/m³)	E / E(BS heavy)	MDD (kg/m³)	OMC (%)	CBR at 2.5 mm (%)	CBR at 5.0 mm (%)	CBR, BS 1377-4 (%)
2.5	27	7.4	443	0.16	1695	12.8	9.6	12.7	12.7
2.5	43	7.4	705	0.26	1740	12.1	16.1	19.7	19.7
2.5	62	7.4	1 017	0.37	1780	11.6	25.8	27.5	27.5
2.5	82	7.4	1 345	0.49	1795	11.4	24.5	26.5	26.5
2.5	100	7.4	1 640	0.60	1800	11.2	26.5	29.6	29.6
4.5	27	19.9	1 196	0.44	1760	11.9	15.0	23.0	23.0
4.5	43	19.9	1 904	0.69	1800	11.6	18.6	28.3	28.3
4.5	62	19.9	2 745	1.00	1860	11.2	24.5	32.7	32.7
4.5	82	19.9	3 631	1.32	1850	11.0	26.3	34.4	34.4
4.5	100	19.9	4 428	1.61	1830	10.8	26.7	29.8	29.8
6.5	27	28.7	1 727	0.63	1785	11.2	25.2	31.1	31.1
6.5	43	28.7	2 750	1.00	1820	11.0	29.1	45.5	45.5
6.5	62	28.7	3 966	1.44	1868	10.8	30.5	37.8	37.8
6.5	82	28.7	5 245	1.91	1850	10.6	26.4	35.6	35.6
6.5	100	28.7	6 396	2.33	1840	10.4	26.0	30.4	30.4
8.5	27	37.5	2 258	0.82	1810	11.2	36.4	45.8	45.8
8.5	43	37.5	3 597	1.31	1780	11.0	29.2	39.6	39.6
8.5	62	37.5	5 186	1.89	1770	10.4	32.2	40.9	40.9
8.5	82	37.5	6 858	2.50	1760	10.2	30.3	34.0	34.0
8.5	100	37.5	8 364	3.05	1740	10.0	27.3	34.6	34.6

Note. E = compaction energy per unit volume ($W \cdot h \cdot N \cdot n/V$, with $n = 5$ and $V = 2243$ cm³); E(BS heavy) = 2745 kJ/m³ (4.5 kg rammer, 450 mm drop, 62 blows). CBR at 2.5 mm and 5.0 mm read from the penetration curves (Figure 5A); the BS 1377-4 value is the higher of the two.

Maximum dry density

Figure 1a shows the MDD against the number of blows for each rammer; the individual compaction curves are given in Figure 4. With the 2.5 kg rammer, MDD increased from 1695 kg/m³ at 27 blows to 1800 kg/m³ at 100 blows, but the rate of increase became small beyond about 62 blows. With the 4.5 kg and 6.5 kg rammers, MDD increased up to 62 blows, reaching 1860 kg/m³ and 1868 kg/m³, respectively, and then decreased slightly to 1830 kg/m³ and 1840 kg/m³ at 100 blows. With the 8.5 kg rammer, MDD was highest at 27 blows (1810 kg/m³) and decreased continuously to 1740 kg/m³ at 100 blows.

Across all 20 combinations, MDD ranged from 1695 kg/m³ (2.5 kg rammer, 27 blows) to 1868 kg/m³ (6.5 kg rammer, 62 blows). The MDD obtained with the 4.5 kg rammer at 62 blows (1860 kg/m³) matched the value obtained for the original material under BS heavy compaction, which corresponds to the same energy level.

The two highest values (1860 and 1868 kg/m³) differ by less than the spread of the triplicate BS heavy tests on the original material (1840, 1860 and 1890 kg/m³), so the 4.5 kg and 6.5 kg rammers at 62 blows should be regarded as giving the same maximum density. Plotted against energy per unit volume (Figure 2a), MDD was not a single function of energy: at 2.2–2.75 MJ/m³, for example, MDD was 1810 kg/m³ with the 8.5 kg rammer at 27 blows, 1820 kg/m³ with the 6.5 kg rammer at 43 blows and 1860 kg/m³ with the 4.5 kg rammer at 62 blows.

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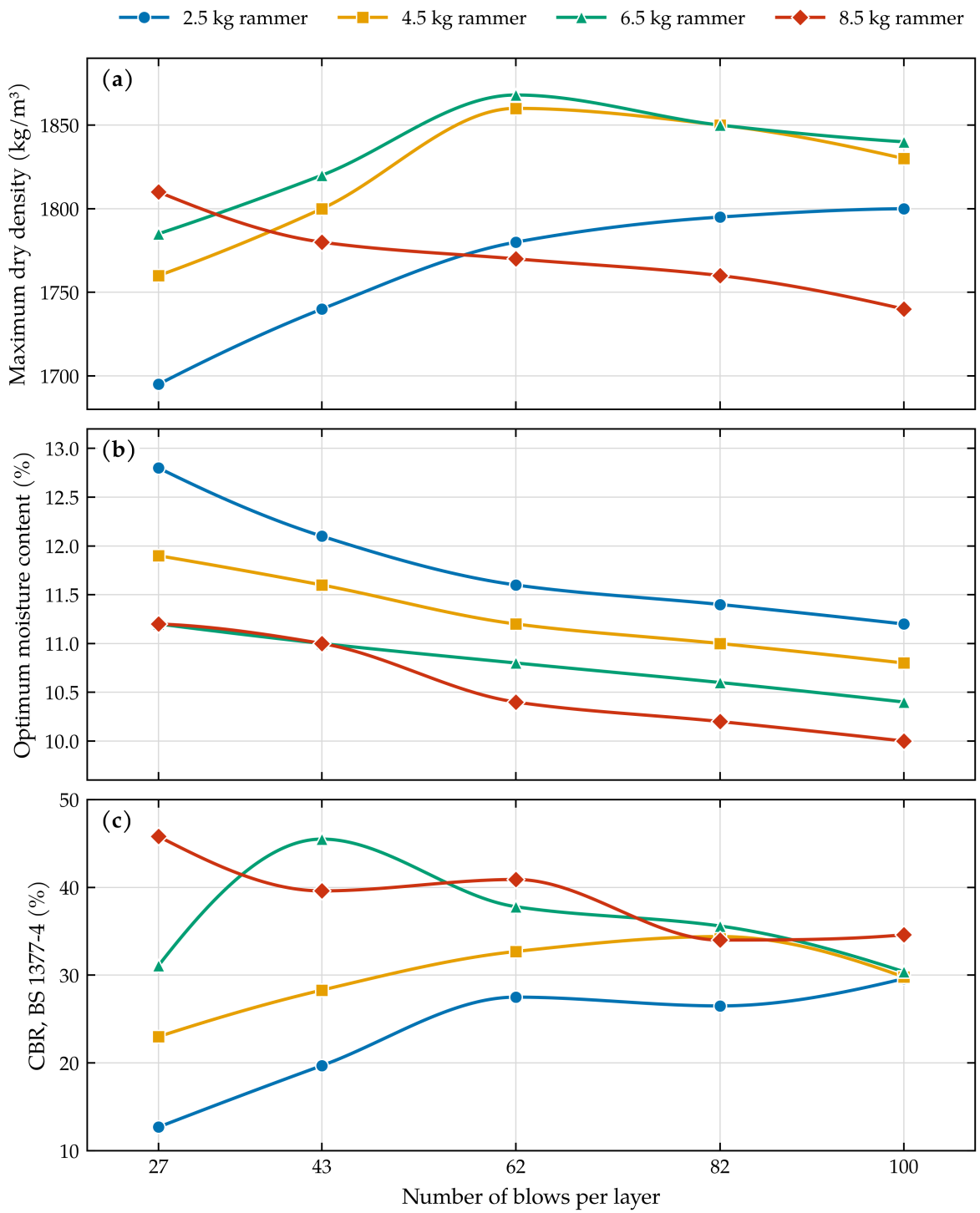


Figure 1. (a) Maximum dry density, (b) optimum moisture content and (c) California Bearing Ratio (BS 1377-4: higher of the 2.5 mm and 5.0 mm values) of the gravel at different rammer weights and numbers of blows (MDD and OMC data previously reported in Makindi et al., 2026)

Optimum moisture content

OMC decreased with increasing number of blows for all rammer weights and was generally lower for heavier rammers at the same number of blows (Figure 1b; Figure 4A). Between 27 and 100 blows, OMC decreased from 12.8% to 11.2% for the 2.5 kg rammer, from 11.9% to 10.8% for the 4.5 kg rammer, from 11.2% to 10.4% for the 6.5 kg rammer and from 11.2% to 10.0% for the 8.5 kg rammer.

California Bearing Ratio

Figure 1c presents the CBR, calculated in accordance with BS 1377-4 as the higher of the 2.5 mm and 5.0 mm values, against the number of blows; the penetration curves are given in Figure5A and all values in Table 2. For the 2.5 kg rammer, CBR increased from 12.7% at 27 blows to 27.5% at 62 blows and changed little thereafter (26.5–29.6%). For the 4.5 kg rammer, CBR increased to a maximum of 34.4% at 82 blows and fell to 29.8% at 100 blows. For the 6.5 kg rammer, CBR peaked at 45.5% at 43 blows and declined steadily to 30.4% at 100 blows. For the 8.5 kg rammer, CBR was highest at 27 blows (45.8%) and fell to 34.0–34.6% at 82–100 blows. At a given number of blows, CBR generally increased with rammer weight, although the differences narrowed at 100 blows (29.6–34.6%).

Overall, CBR ranged from 12.7% (2.5 kg rammer, 27 blows) to 45.8% (8.5 kg rammer, 27 blows), and an almost identical maximum (45.5%) was obtained with the 6.5 kg rammer at 43 blows. The number of blows at which CBR peaked decreased from 100 and 82 blows for the 2.5 kg and 4.5 kg rammers to 43 blows for the 6.5 kg rammer and 27 blows for the 8.5 kg rammer. Expressed as energy (Table 2; Figure 2b), the CBR peaks of the three heavier rammers occurred at about 3.6 MJ/m³ (4.5 kg), 2.75 MJ/m³ (6.5 kg) and 2.26 MJ/m³ (8.5 kg), so the energy at which CBR peaked fell as the energy per blow increased. At similar total energy, CBR was higher with the heavier rammer: at about 2.75 MJ/m³ the 6.5 kg rammer at 43 blows gave 45.5%, against 32.7% for the 4.5 kg rammer at 62 blows.

The two-way ANOVA of the triplicate CBR results (Table 3) showed that rammer weight, number of blows and their interaction all had significant effects ($p < 0.001$; $R^2 = 0.998$). The significant interaction confirms that the effect of the number of blows depended on the rammer weight: CBR increased with blows for the lighter rammers and decreased with blows for the 8.5 kg rammer. Regression showed that the logarithm of energy per unit volume alone explained less than half of the variation in CBR ($R^2 = 0.47$). Adding rammer weight as a second predictor raised R^2 to 0.60, and at a given energy CBR increased by about 1.8 percentage points per kilogram of rammer weight ($p < 0.001$). Replicate CBR values for each combination agreed closely (standard deviation ≤ 0.9 percentage points).

Table 3: Two-way analysis of variance of the triplicate CBR results

Source	Sum of squares	df	F	p	Partial η^2
Rammer weight	1734.8	3	4185	< 0.001	0.997
Number of blows	320.8	4	580	< 0.001	0.983
Rammer weight × number of blows	984.7	12	594	< 0.001	0.994
Residual	5.5	40			

Note. Analysis of the CBR index recorded for the three specimens of each combination (n = 60).

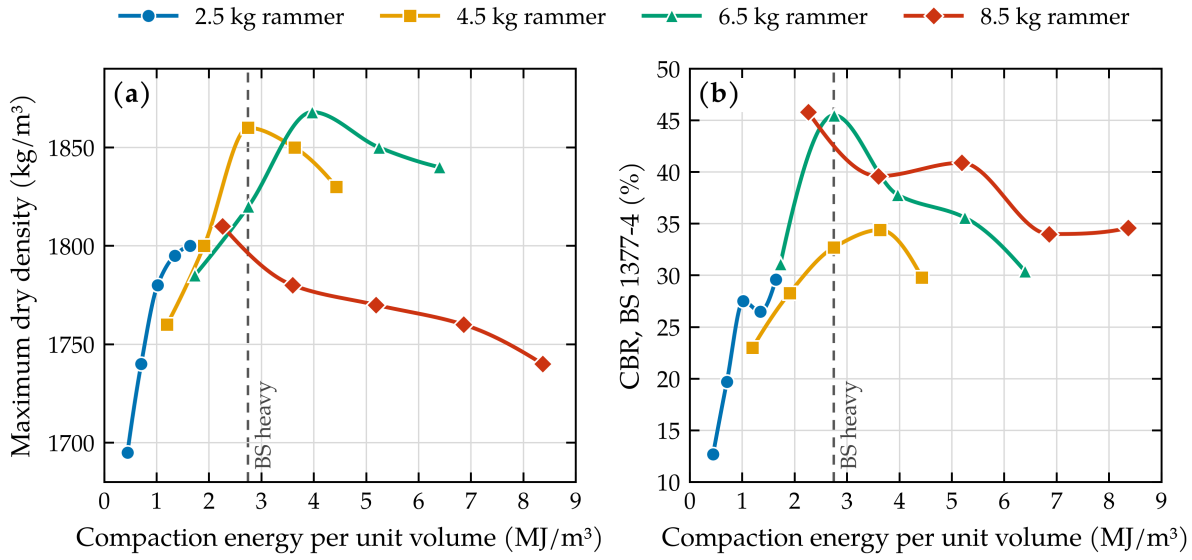


Figure 2: (a) Maximum dry density and (b) CBR (BS 1377-4) of the gravel plotted against compaction energy per unit volume for each rammer weight; the dashed line marks the BS heavy compaction energy (2745 kJ/m³)

Discussion

Effect of compaction energy on plasticity

The gradual reduction in PI with increasing number of blows is attributed to particle breakage under higher compaction forces, which modifies the soil structure (Chen et al., 2021). Crushing of coarser particles produces additional fines, but these newly formed fines often have low plasticity (Irani et al., 2025). As the proportion of such fines increases, the composition of the soil changes and its capacity for plastic behaviour decreases (Zhang & Buscarnera, 2015). The results therefore show that the plasticity of the gravel is sensitive to intensive compaction, in which excess energy causes microstructural changes through particle fragmentation (Chen et al., 2018). Because rammer weight had little effect on PI at a given number of blows, the number of load repetitions appears to have influenced plasticity more than the weight of the rammer within the range tested.

These changes have practical significance for material acceptance. The PI of the original gravel (17%) exceeded the recommended maximum of 12% for G25 natural gravel sub-base (MoW, 1999) and although compaction reduced the PI to 13–14% at 100 blows, it remained above this limit. A reduction in PI after heavy compaction should therefore not be interpreted as an improvement in material quality, because it results from the breakdown of particles rather than from a change in the nature of the original fines.

Effect of compaction energy on density and moisture content

At low numbers of blows, particles rearrange, interlock and pack more closely, and internal frictional resistance increases with packing density; voids are therefore reduced efficiently and MDD increases (Chengula, 2023). For the 2.5 kg rammer, the energy remained low enough for this process to continue up to 100 blows, although the gain in density became small, indicating diminishing returns. For the 4.5 kg and 6.5 kg rammers, the optimum was reached at 62 blows; beyond this point, over-compaction generated fines and reduced densification. For the 8.5 kg rammer, MDD was highest at 27 blows (2.26 MJ/m³), although this energy is lower than the energies at which the 4.5 kg and 6.5 kg rammers reached their maximum density (2.75 and 3.97 MJ/m³). This indicates that the energy delivered per blow (37.5 J for the 8.5 kg rammer), and not

only the total energy, controls when particle breakage begins: heavier impacts crush particles from the first blows, so additional blows mainly cause further breakage and loss of density. As the fines content increases, the soil structure becomes less stable and more compressible, which reduces its ability to achieve a high dry density (Chen et al., 2018). These findings show that there is an optimum range of compaction energy beyond which additional energy is counterproductive, that this range depends on the energy per blow, and that identifying this range is important for achieving maximum compaction in the field without compromising the integrity of the compacted gravel (Akter et al., 2025).

The decrease in OMC with increasing compaction energy reflects the closer packing of particles, which reduces the need for water to lubricate particle movement and rearrangement. Higher-energy allows particles to overcome internal friction and pack more tightly with less reliance on water, while particle breakage further modifies the soil structure so that MDD is reached at a lower moisture content (Akter et al., 2025; Lillian et al., 2025). Higher compaction energy therefore shifts the OMC to lower values and reduces the amount of water required for compaction.

Effect of compaction energy on CBR

The initial increase in CBR with the number of blows for the 2.5 kg and 4.5 kg rammers is attributed to densification of the soil matrix, in which particle rearrangement, interlocking and frictional resistance produce a stronger structure that resists penetration. For the 4.5 kg rammer, the drop at 100 blows is likely due to the onset of particle degradation and the generation of fines, which reduce the internal friction and stiffness of the compacted soil. For the 6.5 kg rammer, the peak occurred at fewer blows (43) and the subsequent decline was more pronounced, consistent with particle degradation and increased fines content reducing internal friction and shear strength (Basack et al., 2021). For the 8.5 kg rammer, the continuous decrease in CBR is attributed to the crushing of particles under repeated heavy impacts (Beddu et al., 2018), which reduces inter-particle friction and load resistance (Youventharan et al., 2021; Zhang & Buscarnera, 2015).

Taken together, the MDD and CBR results indicate that each rammer weight has an optimum number of blows and that this optimum moves to fewer blows as the rammer weight increases. The highest CBR (45.8% with the 8.5 kg rammer at 27 blows and 45.5% with the 6.5 kg rammer at 43 blows) was obtained at 2.3–2.8 MJ/m³, whereas the highest MDD (1860–1868 kg/m³ with the 4.5 kg and 6.5 kg rammers at 62 blows) was obtained at 2.7–4.0 MJ/m³, showing that maximum strength and maximum density did not occur under the same compaction conditions.

Why maximum density and maximum bearing capacity do not coincide

Across the 20 combinations, MDD and CBR were only moderately correlated ($r = 0.51$), and the combination with the highest CBR (8.5 kg rammer, 27 blows) had an MDD of 1810 kg/m³, 50–58 kg/m³ below the maximum. This has a direct engineering meaning: a layer that reaches the highest laboratory density is not necessarily the layer with the highest bearing capacity, so a density target on its own does not guarantee strength. Four mechanisms, acting together, can explain the difference.

First, the two tests measure different things. Dry density measures how much solid material is packed into the mould, whereas CBR measures resistance to a penetrating plunger, which depends mainly on the shear resistance of the coarse skeleton through particle interlock and inter-particle friction. Fines produced by crushing can fill the voids between coarse particles and keep the density high while the same crushing rounds and weakens the coarse particles that carry the load, so density can remain high while bearing capacity falls (Youventharan et al., 2021; Zhang & Buscarnera, 2015).

Second, gradation changes with energy. As the fines content increased (from 22% to 50% with the 8.5 kg rammer), the gravel moved from a structure in which load is carried through contacts

between coarse particles towards one in which the coarse particles are separated by a matrix of clayey fines. Once the fines fill and exceed the voids of the coarse fraction, bearing capacity is governed by the weaker fine matrix rather than by the interlocked gravel (Chen et al., 2018).

Third, particle interlock depends on how the energy is delivered. The 8.5 kg rammer at 27 blows applied a few heavy impacts that appear to have forced the coarse particles into a strongly interlocked arrangement before extensive degradation occurred, giving the highest CBR at a moderate density. The 4.5 kg and 6.5 kg rammers reached their highest density only after more blows, by which time more fines had been generated. This is consistent with the higher CBR obtained at similar total energy with heavier rammers (Table 2; Figure 2b).

Fourth, moisture content interacts with the changing grading. OMC fell as energy increased, but the fines generated by crushing have a larger specific surface and hold a greater share of the mixing water; with plastic fines (PI 13–16%), this water lubricates particle contacts and reduces shear resistance at the plunger more than it reduces density. Because particle breakage was not measured directly and fines contents are reported only for the 8.5 kg rammer, these explanations remain inferences that should be confirmed with breakage indices and grading of all compacted specimens.

In the field, the weight of the rammer is broadly analogous to the load applied by a compaction roller, and the number of blows to the number of roller passes. By analogy, the results suggest that heavy compaction plant can achieve high bearing capacity with relatively few passes, and that additional passes with such plant may reduce rather than increase the strength of the gravel. Conversely, lighter plant may require more passes to reach its optimum. Specifying the number of passes together with the type of compaction plant, rather than relying on a density target alone, may therefore help to avoid over-compaction of gravel layers.

Limitations

This study was based on a single gravel material from one borrow pit, so the energy thresholds identified may differ for gravels of different mineralogy, gradation and plasticity. All tests were carried out in the laboratory, and the relationship between the laboratory energy levels and field compaction plant was not established. Particle breakage was inferred from changes in fines content and plasticity rather than quantified with a breakage index, and the CBR at varying energy levels was determined from single-point tests. Further studies should include field trials, other gravel types and quantitative measures of particle breakage. Within the experimental design, rammer weight and number of blows were varied factorially and their main and interaction effects on CBR could be estimated (Table 3). However, for the 2.5 kg series the effects of rammer mass and drop height cannot be separated, and the experiment cannot distinguish rammer mass from energy per blow; MDD and OMC were not replicated. Future work should vary drop height at constant rammer mass and rammer mass at constant energy per blow.

Conclusion

Increasing laboratory compaction energy, through either a heavier rammer or more blows per layer, improved the MDD and CBR of the gravel only up to an optimum, beyond which both properties declined. The highest MDD (1860–1868 kg/m^3) was obtained at 62 blows with the 4.5 kg and 6.5 kg rammers, and the highest CBR (45.8% and 45.5%) with the 8.5 kg rammer at 27 blows and the 6.5 kg rammer at 43 blows, at lower energy than the density peak. The energy at which CBR peaked decreased as the energy per blow increased, so total compaction energy alone does not describe the compaction effort. With the 8.5 kg rammer, increasing the number of blows from 27 to 100 reduced the CBR from 45.8% to 34.6% and increased the fines content from 22% to 50%, showing that excessive compaction causes particle breakage that alters the gradation and plasticity of the material.

OMC decreased for all rammer weights as the number of blows increased, indicating that less water is required to reach MDD at higher compaction energy. PI decreased slightly with increasing number of blows but was hardly affected by rammer weight.

Although compaction is essential for the performance of gravel layers, excessive compaction energy changes the index properties that engineers use to select materials for road construction. Engineers should therefore balance compaction energy and moisture content so that the material reaches the required strength without damage to its properties.

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Appendices

Figure 1A: Excavated material at the Idugumbi borrow pit (left) and material air-drying at the laboratory (right)



Figure 2B: Rammers used in the study



Table 1A: Compaction programme for each rammer weight

Weight of Rammer	**2.5kg**	**4.5kg**	**6.5kg**	**8.5kg**
Number of blows	27	27	27	27
	43	43	43	43
	62	62	62	62
	82	82	82	82
	100	100	100	100
Number of layers	5	5	5	5

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Table 2A: AASHTO classification of the gravel material

Source materials	Physical properties	AASHTO Classification	% Fines	% Sand	% Gravel
Gravel material	Reddish-Brown colour soil	A-2-6 Clayey Gravel	11	28	61

Figure 3A: Properties of the original gravel material: (i) particle size distribution, (ii) compaction curve (BS heavy) and (iii) three-point CBR curve

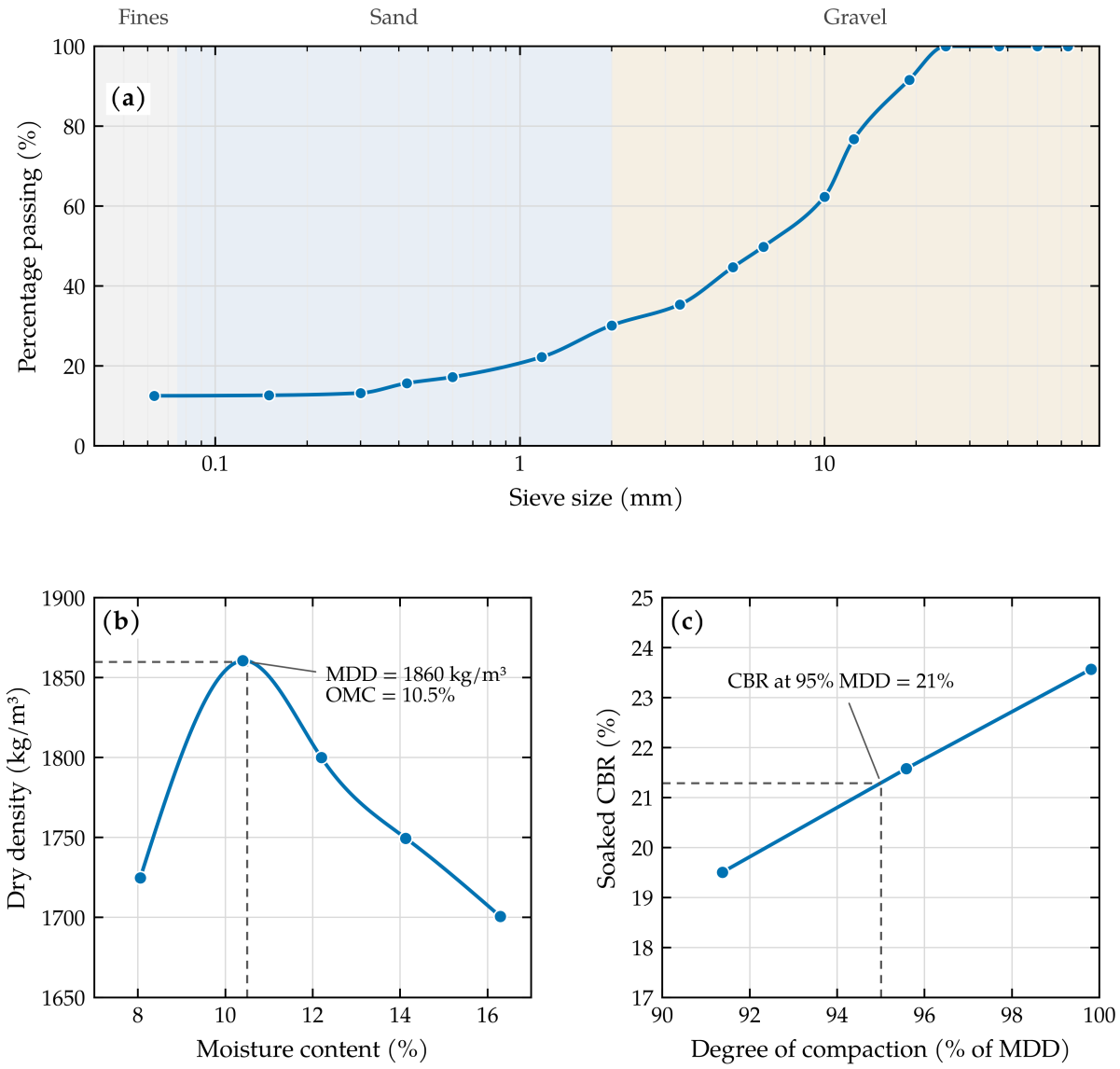
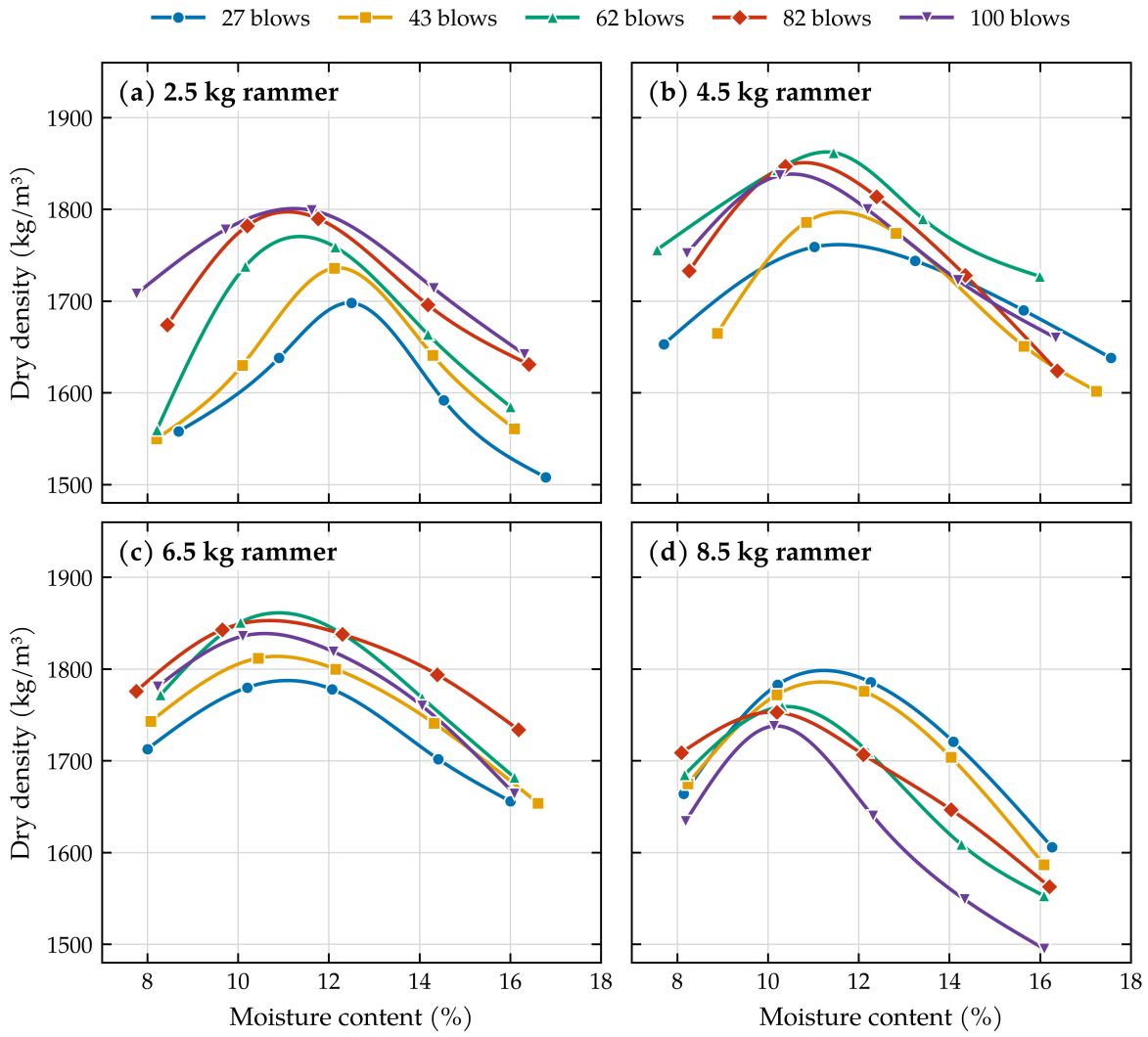


Figure 4A: Dry density–moisture content curves at varying numbers of blows for the (a) 2.5 kg, (b) 4.5 kg, (c) 6.5 kg and (d) 8.5 kg rammers



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Figure 5A: CBR penetration curves at varying numbers of blows for the (a) 2.5 kg, (b) 4.5 kg, (c) 6.5 kg and (d) 8.5 kg rammers; dashed lines mark the 2.5 mm and 5.0 mm penetrations used to calculate CBR

