PREDICTING THE PERFORMANCE OF TYPE 1 SLATE AGGREGATE

by

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1.0 INTRODUCTION

Slate quarrying has been active in Wales for at least the last 400 years. Only rock suitable for splitting into slates is accepted from the quarried stone. There is a waste to final product ratio of 20 to 1 resulting in huge tips of waste material.

Slate waste has been widely used in North Wales for general fill and road building for many years. For example, it was successfully used as sub-base on the A55 coastal road and dualling of the A5 in Anglesey.

Until the introduction of the Aggregates Tax, the cost of transporting slate made it uncompetitive with primary quarried aggregate. However, slate is now a commercially viable construction material despite its location.

Greater use of slate would help satisfy the need for increasing use of recycled and secondary materials. Local authorities should be considering its use. However, there has been little historical use of slate outside of North Wales.

Engineers are reluctant to use what is regarded as sub-standard, flaky aggregate. It is assumed that the aggregate particles are not strong, that is not durable and will not compact.

The research detailed in this report aims to address these fears and considers the performance of slate as an unbound Type 1 aggregate.

The report first considers basic properties such as physical and mechanical properties. It considers the effect of moisture content on density, compaction and layer thickness.

The findings of a wheel-tracking test are discussed that has been developed to predict permanent deformation and load bearing properties of sub-base material.

The report details laboratory and field correlation of compaction measured using Nuclear Density Meter, California Bearing Ratio (CBR) and Clegg Impact Value (CIV).

The report concludes by recommending a conversion table that predicts Equivalent %CBR based on Clegg Impact Value measured onsite.

2.0 PREDICTING THE PERFORMANCE OF UNBOUND SLATE

Deformation of an unbound layer will cause problems with overlying layers. This can be reduced if measures are taken to use high quality aggregate, achieve good compaction, use thick aggregate and asphalt layers to reduce the stresses.

However, reliance on thicker layers makes a design un-economical. There is now considerable pressure to recycle and use secondary aggregates. However, many of these recycled unbound materials have either never been or have had limited use in the UK until the past few years e.g. unbound C&D waste.

There are many millions of tonnes being used despite the problems of variability, sorting and relatively poor properties. Specification requirements now accommodate an increasing range of options of what would formally have been regarded unsuitable.

Slate waste, a secondary aggregate from an industrial process, is one such material that has proven very successful locally over many years in North Wales and shown in the laboratory to perform well. Being from a consistent, unvarying source, relatively inert and durable means the aggregate can perform well in-situ.

However, when slate travels out of North Wales it is being used by engineers with relatively little past experience of such a flaky aggregate. When tested in-situ using established methods such as Clegg, the impact of the hammer dropping on the surface may give a different impression of its compaction compared to a more conventional type of aggregate.

This report has considered how the performance of slate may be predicted and details an investigation using standard and non-standard testing.

2.1 BASIC SLATE AGGREAGATE PROPERTIES

Slate is a fine-grained metamorphic rock originating from mudstones and siltstones. XRF analysis gives its composition to be about 60% silica, 20% alumina and 8% iron, with minor amounts of MgO (3%), Na_2O (2%) and K_20 (3%).

When viewed under the microscope in thin-section the individual grains are difficult to determine due to their fine to micro-crystalline size. Muscovite and chlorite is also present formed within the matrix during low-grade metamorphism.

The result of this mineralogical composition is a hard, durable material that is effectively inert and will not change during its engineering life. For example, Welsh slate is famed around the world as being the best quality and most durable roofing product available.

Table 2.1 shows Penrhyn slate data for a range of tests typically used to classify suitability of aggregate for use in road construction. The data clearly shows that slate has properties comparable to high quality aggregate used in highway construction. One of its weaker properties is the relationship between particle shape and laboratory measured strength.

It should be pointed out that there are examples of aggregates with much lower strength values than slate performing adequately in-situ. One must always distinguish the difference between the limitations of any test method, both in the laboratory and in the field with actual performance. In certain cases, a test may be aggregate or material specific and give misleading results.

The data in Table 2.1 shows that slate can meet all the requirements of an unbound aggregate. It should be pointed out that there is no requirement for flaky aggregate in the UK specification for Type 1 and Type 2 unbound aggregate.

Figure 2.1 shows the grading curve of a sample of slate sampled at Penrhyn. This shows the slate to be coarse graded meeting both the Type 1 and 2 grading requirements.

Based on these physical and mechanical properties, slate waste is suitable as unbound aggregate.

Table 2.1 Test data for Penrhyn slate

Test	Units	Value reported
Apparent relative density	Mg/m^3	2.86
Oven dried relative density	Mg/m^3	2.84
Saturated surface dry relative density	Mg/m^3	2.85
Water absorption	%	0.30
Aggregate abrasion value		12.4
Aggregate impact value	%	30
Aggregate crushing value	%	24
Ten percent fines value (dry)	kN	120
Ten percent fines value (wet)	kN	100
Frost heave (DTP)	mm	8.2
Magnesium sulphate soundness	%	96
Frost susceptibility		Non susceptible
Soluble sulphate content	g/litre	<0.01
CBR	%	123
GSB Type 1 Uniformity Coefficient		>10
Uncompacted bulk density	Mg/m^3	1.79

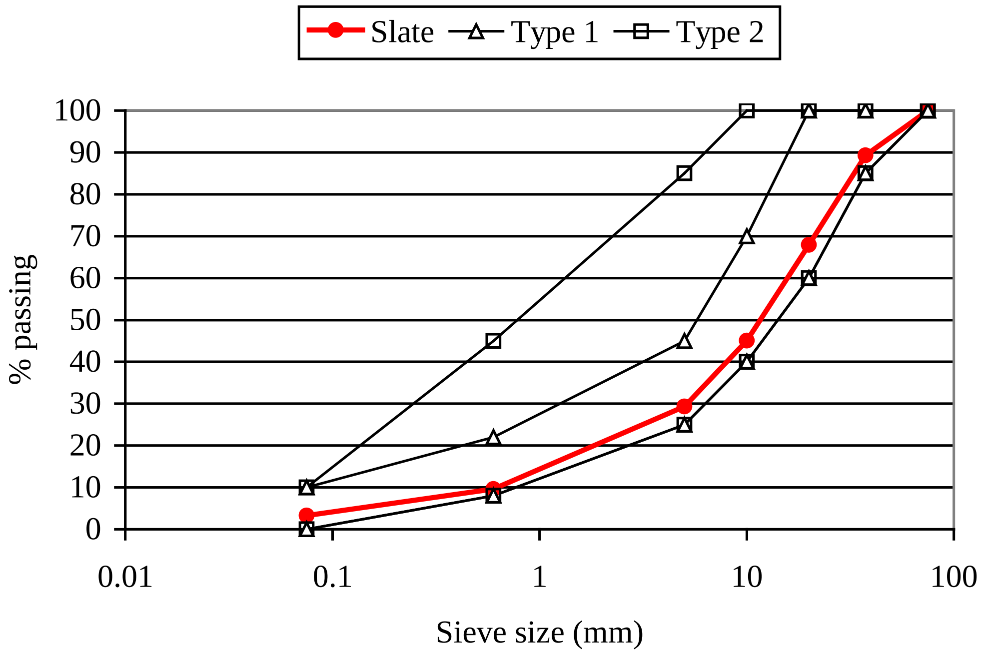


Figure 2.1 Particle size distribution for Penrhyn slate showing Type 1 and Type 2 grading limits

2.2 EFFECT OF MOISTURE CONTENT ON COMPACTING SLATE TYPE 1 AGGREGATE

A simple experiment was carried out to see the effect of moisture content on the wetting of slate particles subject to compaction. Centre grading Type 1 test samples of 5000g dry mass were prepared. Sufficient water was added to make a range of moisture contents from 0 to 10%. These were subjected to 500 gyrations using a gyratory compactor.

This method of laboratory compaction has the benefit of recording change in properties such as compacted height, density and void content during compaction and is a direct method of comparing different materials during the compaction process.

The extracted sample was then assessed visually to determine the effect of moisture content. Table 2.2 is a simple description of the compacted material. At about 5% moisture, free moisture was starting to appear at the base of the mould during extraction. At the higher moisture contents, excess water was left in the plastic bag. This suggests slate to have a relatively low Optimum Moisture Content.

Table 2.2 Description of wetted slate after compaction

Amount of moisture added (%)	Comments
0.5	Little change, particles appear dry
1	Approximately half damp
2	Most larger aggregate coated, extracted sample just holding shape
3	Aggregate well coated, extracted sample quite solid, some free moisture
4	Aggregate well coated, free moisture apparent on outside of extracted sample
5	Free moisture appearing at base of extracted test sample
10	Excess moisture left in plastic bag prior to compaction

2.3 EFFECT OF GRADING ON COMPACTION

Unbound aggregates may become segregated. When used on-site differential compaction may later cause problems with the finished highway. Previous research at the University of Ulster has shown different aggregate types and gradings to result in problems such as the migration of plastic fines.

A bulk sample of slate was sieved to obtain single size aggregate. The single sizes were combined to form 5000g test samples with a grading corresponding to the coarse and fine Type 1 limits given in Table 2.3.

The graded test specimens were placed in plastic bags and 4% water by mass added. The bags were sealed and left for 24 hours to allow the water to absorb into the unbound aggregate.

The test samples were placed in a 150mm gyratory compactor mould, filled in two layers, tamped and their weight recorded. Each test sample was compacted for 500 gyrations using a gyratory compactor.

Table 2.4 shows test specimen height and density after 500 gyrations for coarse, fine and as received test samples. Figure 2.2 plots the change in density of test samples at 4% moisture for prepared coarse, fine and as received test samples.

Figure 2.2 shows that the coarse graded test samples produce a slightly denser material. However, after 500 gyrations the difference in density between the two grading limits is less than 5%. Table 2.4 shows that the finer graded material results in a compacted layer that is 6mm thicker.

Table 2.3 Coarse and fine gradings based on Type 1

BS sieve size (mm)	% by mass passing			
	Type 1 limits	As received	Coarse grading	Fine grading
75	100	100	100	100
37.5	85-100	89	85	100
20	60-100	68	60	100
10	40-70	45	40	70
5	25-45	29	25	45
0.6	8-22	10	8	22
0.075	0-10	3	0	10

Table 2.4 Compaction data after 500 gyrations

	Moisture content (%)	Height (mm)	Density (kg/m^3)
Coarse grading	4	119	2478
Fine grading	4	125	2364
As received	4	124	2375

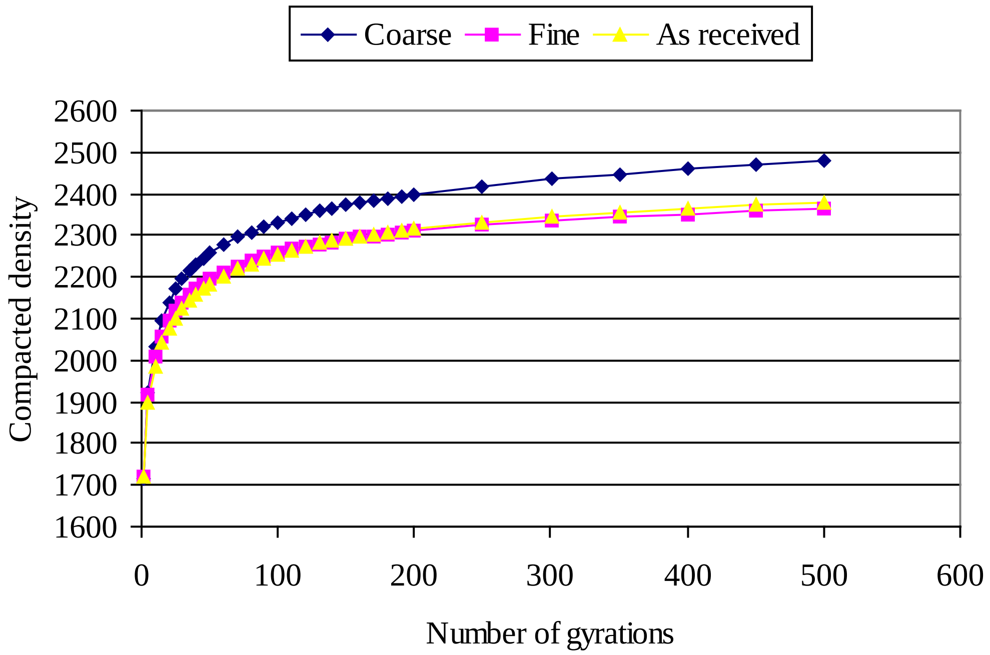


Figure 2.2 Change in density during gyratory compaction

2.4 EFFECT OF MOISTURE CONTENT ON COMPACTION

Increasing moisture in a pavement can have a disruptive effect on the integrity of the unbound layer. The effect of increasing amounts of moisture was investigated using gyratory compaction. The slate waste was dried to constant mass in an oven maintained at 105^0C.

After cooling 5000g test samples were obtained by riffling. These were placed in individual plastic bags along with sufficient water to produce a range of moisture contents from 0 to 10% of dry mass. The bags were sealed and the moisture allowed to absorb into the loose aggregate for 24 hours.

The saturated slate was re-weighed prior to placement in a 150mm diameter gyratory compactor mould. The aggregate was placed in two layers with each layer receiving 12 tamps from a steel bar. Each sample was compacted for 500 gyrations.

Table 2.5 shows a summary of actual moisture content, void content, density and layer reduction data obtained after 500 gyrations for each increment in moisture content.

Figure 2.3 plots the change in void content with increasing number of gyrations for each moisture content. Figure 2.4 plots change in density with increasing number of gyrations. It can be seen that there are general relationships between the 3 variables involved.

Void content decreases with increasing number of gyrations or compactive effort. For any given degree of compaction, the void content decreases with increasing moisture content.

Table 2.5 Summary of gyratory compaction data after 500 gyrations

Moisture content (%)	Actual moisture content (%)	Void content (%)	Density	Layer reduction (%)
0	0.02	27.2	2087	20.9
1	1.0	25.9	2123	19.8
2	2.02	22.8	2211	23.3
3	2.92	16.8	2382	25.4
4	3.86	17.1	2375	27.6
5	4.44	17.0	2377	28.4
6	5.22	18.8	2327	27.2
7	6.62	17.4	2365	25.2
8	7.34	12.3	2512	28.3
9	7.82	11.2	2543	29.4
10	9.12	11.7	2530	24.8

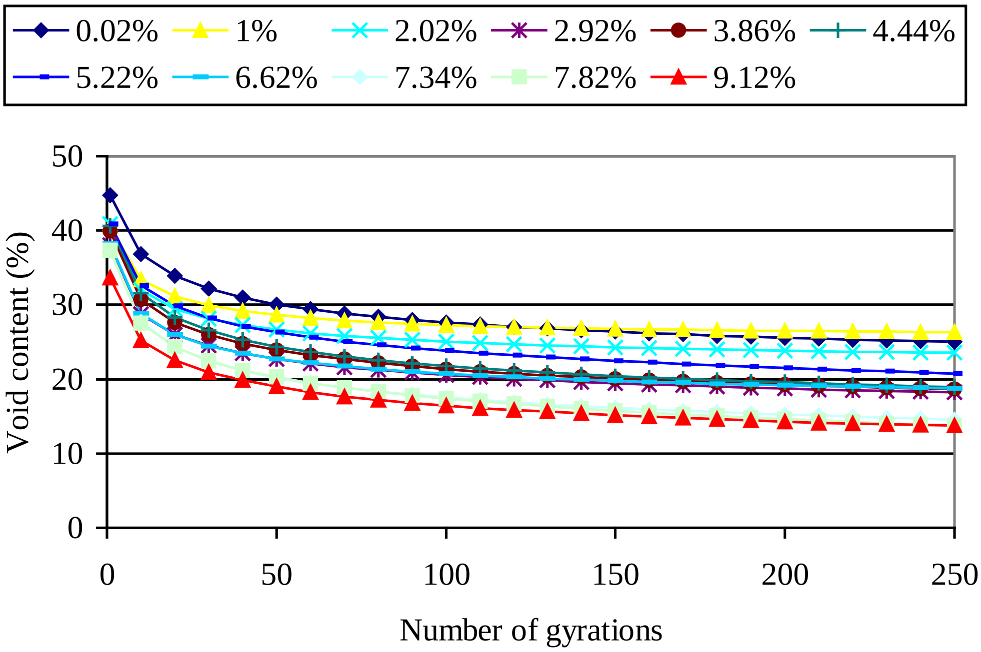


Figure 2.3 Change in void content during gyratory compaction

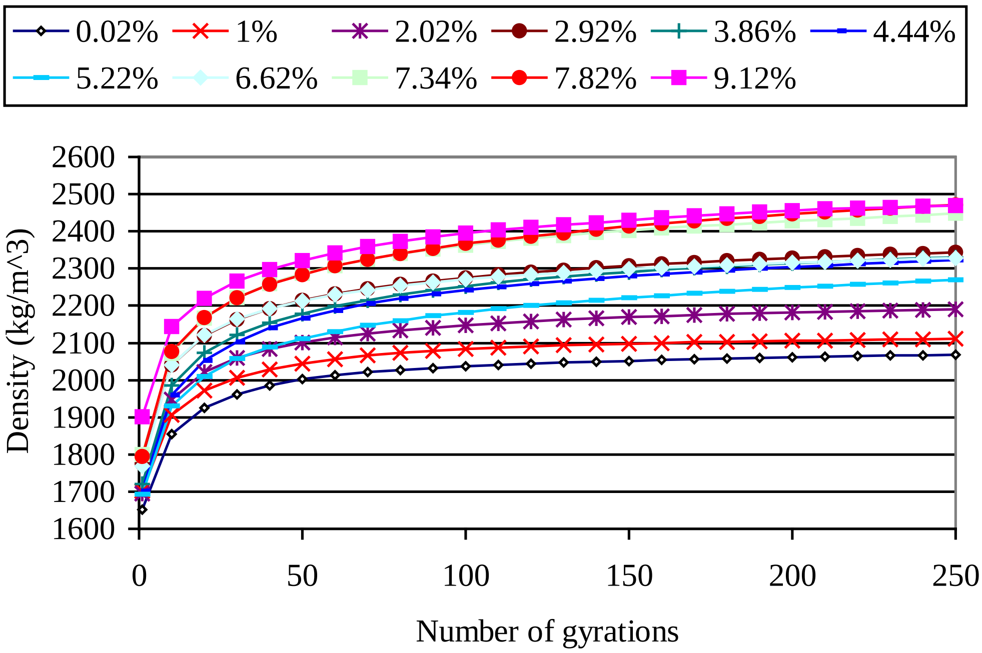


Figure 2.4 Change in density during gyratory compaction

Figure 2.4 shows the relationship between density and moisture content for increasing number of gyrations. This shows density to be related to moisture content and degree of compaction. Figure 2.5 shows the relationship between layer reduction and moisture content during gyratory compaction.

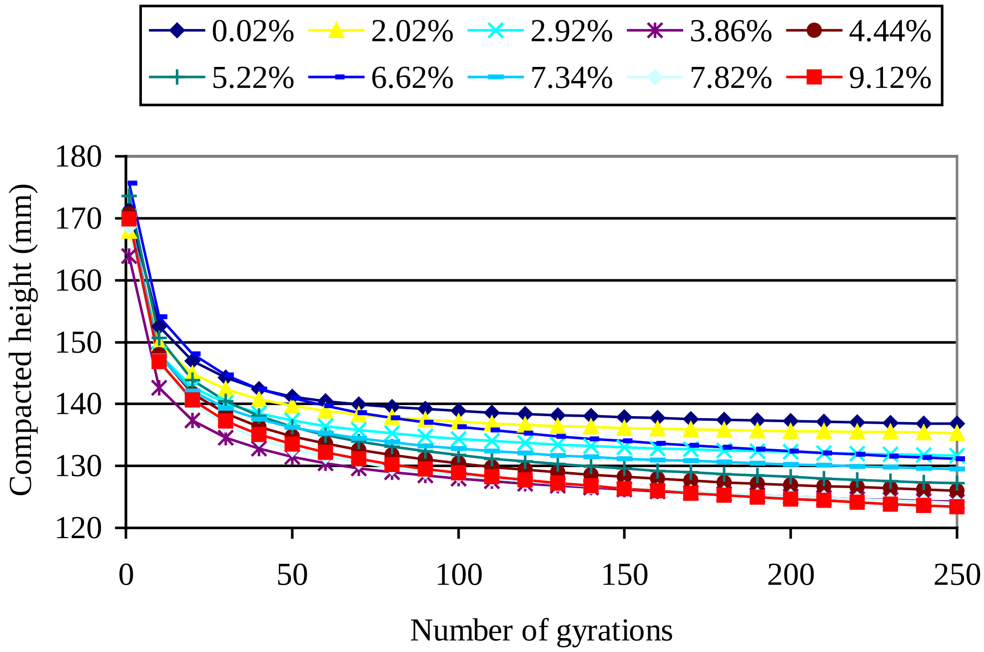


Figure 2.5 Change in compacted height during gyratory compaction

A plot of initial moisture content and density after 250 gyrations is shown in Figure 2.6. This shows a peak in the plot corresponding to a moisture content ranging from 3 to 4.5%. A second peak occurs with moisture contents ranging from 7.5 to 9%.

It should be noted that at the higher moisture contents excess water was observed to be squeezed out of the base of the gyratory mould during compaction. It should also be noted that levels of compaction achieved on-site would probably be less than those obtained in the confined mould during laboratory compaction.

Figure 2.6 suggests that optimum density is achieved at moisture contents around 3 to 4%. There is a secondary peak in the data at approximately 8%. During filed compaction trials it was found that greatest wet density measured using both nuclear Density Meter and Clegg Impact Value corresponded to this moisture content.

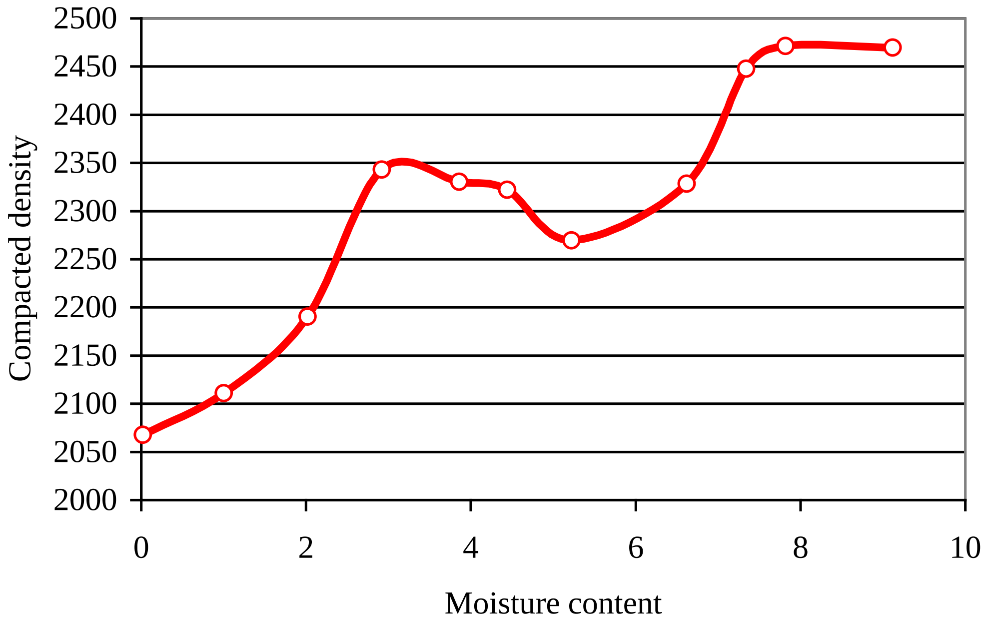


Figure 2.6 Density after 250 gyrations for increasing moisture content

2.5 COMPARISON OF IMPACT AND KNEADING COMPACTION

Gyratory compaction was used during the initial laboratory investigations, as it is more controllable than other types such as Marshall or vibratory methods. For example, the change in density and height with number of gyrations is stored during testing and can be used for later evaluation.

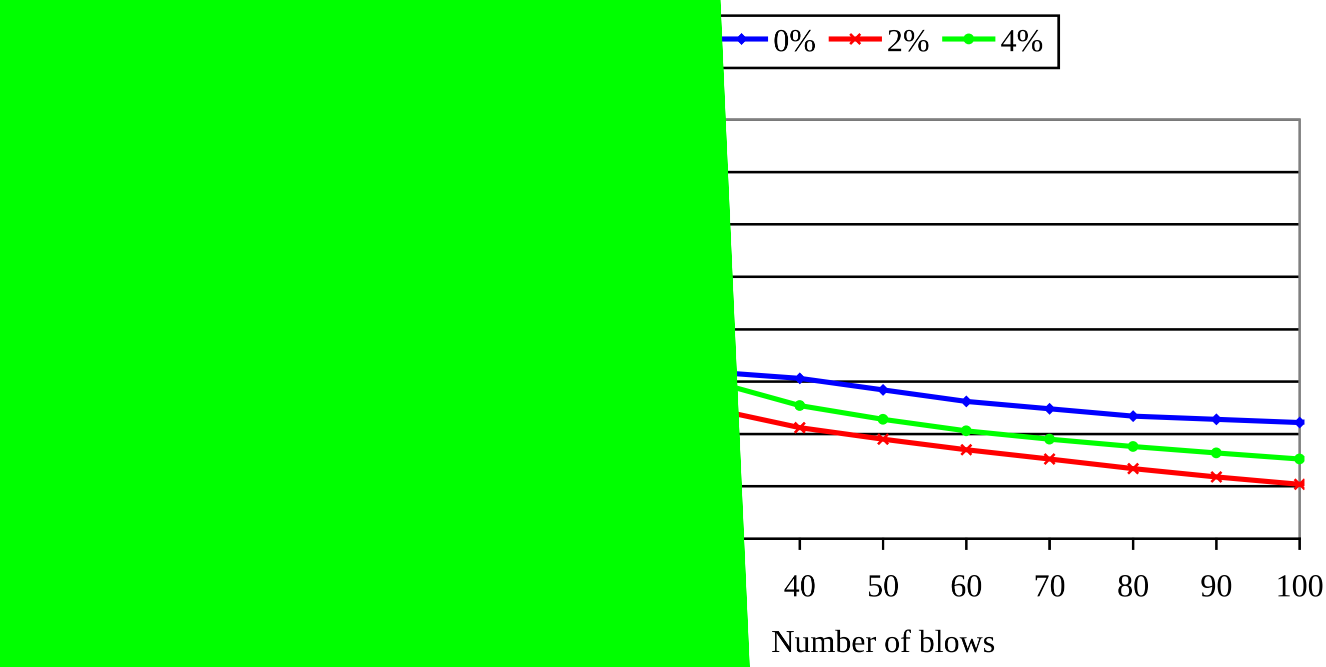
It is generally believed that the kneading action caused during gyratory compaction better simulates the action of a roller than the sudden impact of Marshall or aggressive kango vibration.

However, it was considered that an alternative method of laboratory compaction be assessed. Marshall impact was chosen as it was felt to offer less change in grading due to particle breakage compared to Kango vibration.

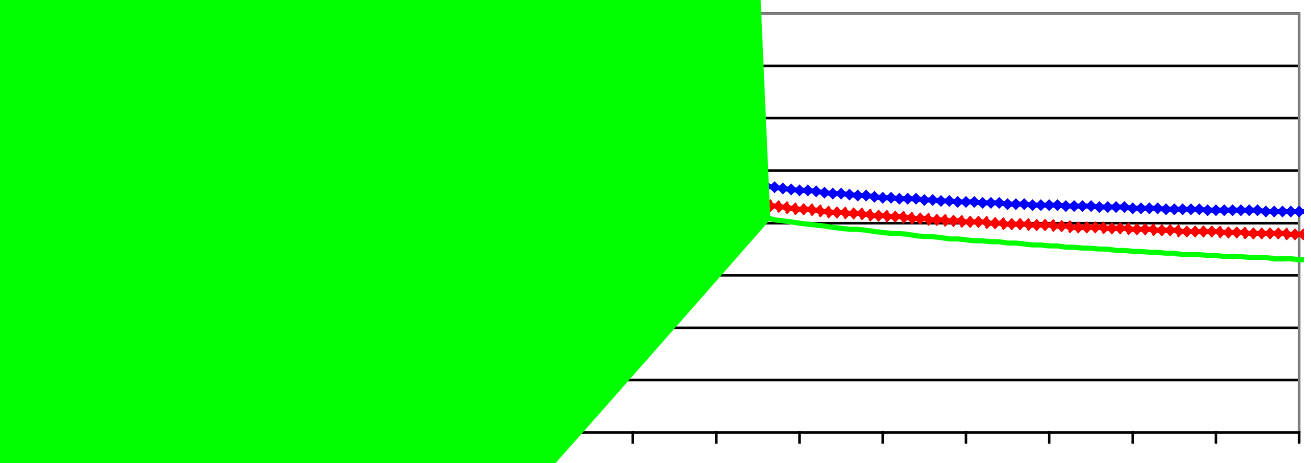
The reduction in layer thickness due to compactive effort was assessed. This gives information regarding the possible reduction in layer thickness during rolling or other types of compaction.

Figures 2.7 and 2.8 compare the percentage reduction in layer thickness for test specimens at 0, 2 and 4% moisture content using Marshall impact and gyratory kneading respectively.

They show that slate will compact at different rates depending on the method of compaction used i.e. it appears to compact quicker using impact compaction.



ompacted height due to number of blows



2.6 ASSESSMENT OF CONSTRUCTION AND POST DEFORMATION

Post compaction of unbound layers will cause problems with over lying layers. A simple wheel-tracking test was used to simulate stress conditions that could result in permanent deformation under a moving wheel load.

The majority of reported research using wheel track testing has been for bituminous materials. This test was originally developed to simulate the rutting of hot rolled asphalt in road surfaces. For example, good correlation was found between surface deformation and the wheel tracking rate of HRA wearing course.

The standard dry equipment used to test bituminous materials was not suitable to investigate unbound materials. Rather, an immersion wheel tracker was modified to enable the testing of compacted unbound test samples.

A steel box 300mm x 420mm x 200mm (wide x length x depth) was designed to hold the compacted unbound aggregate material for testing. This was used to simulate a layer thickness of 100mm. A rigid concrete layer 100mm thick was placed below the unbound layer to give a very strong bearing capacity.

Rutting that occurs in the unbound base layer is therefore not effected by the layer below it. A 20kg load was used to give a wheel pressure approximately equal to the contact pressure of a single wheel of $7kg/cm^2$.

Room temperature of 20°C was used as the unbound base material was not sensitive to temperature. The number of load applications (wheel passes) applied was 5000. Slate waste was compared to three unbound aggregates of centre specification Type 1 grading envelope at optimum moisture content.

- Aggregate LS was basalt with non-plastic fines and had the lowest Optimum Moisture Content of 5.85%. It is regarded as being one of Northern Irelands best quality basalts.
- Aggregate BM was basalt with fine aggregate sensitive to moisture and a Plasticity Index of 15.1%.
- Aggregate WM was basalt with poor Los Angeles value and Plasticity Index of 12.2%.

The wetted material was mixed thoroughly by hand, weighed and stored in sealed plastic bags. Sufficient material to give a compacted layer thickness of 100mm was emptied into the steel container, avoiding segregation, and then subjected to vibratory compaction until approximately 95-100% dry density was achieved.

Each test specimen was subjected to wheel-tracking and rut depth recorded from the middle of the rut located in the centre of the box. The total depth of rutting for each specimen is shown in Table 2.6 and plotted in Figure 2.9.

Table 2.6 Comparison of wheel track data

Source	Optimum Moisture Content (%)	Moisture content (%)	Rut depth after 5000 passes (mm)
LS	5.85	-	3.73
BM	7.80	-	13.36
WM	10.20	-	19.6
Slate	-	0	3.08
Slate	-	4	2.87

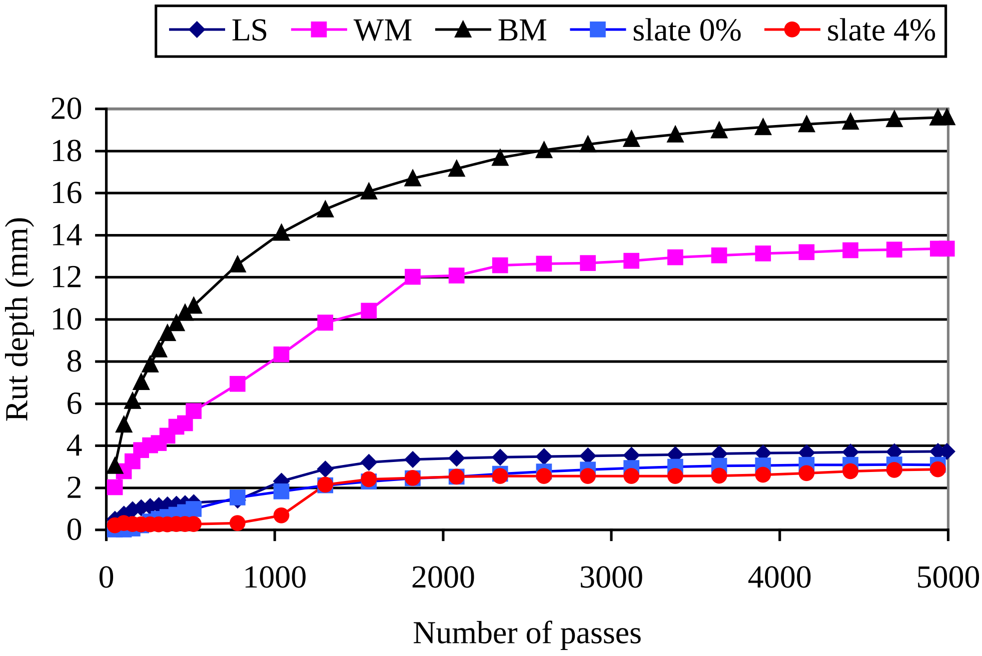


Figure 2.9 Plot of rut depth with increasing number of wheel passes

The results show slate at both 0 and 4% to be comparable in performance to the best basalt aggregate assessed. This is despite its flaky particle shape characteristics.

The two remaining basalt aggregates were chosen to demonstrate the ability of this wheel tracking test to discriminate between aggregates in terms of performance. This testing clearly shows slate to have good performance in terms of resistance to permanent deformation and load bearing properties.

3.0 LABORATORY CORRELATION BETWEEN CLEGG IMPACT VALUE AND CBR

The assessment of density and strength properties of unbound granular materials used to construct road bases, sub bases and trench reinstatements is critical for good design practice.

The California Bearing Ratio (CBR) test is used extensively for assessing these properties. However, the test is time consuming and expensive especially when carried out on site.

The Clegg Impact Tester is a fast and inexpensive alternative to CBR testing (Deakin 2001). Research by Clegg (1980), Mathur and Coglans (1987) and Al-Moudi et al (2002) have shown Clegg Impact Value (CIV) to correlate well with CBR for a wide range of materials.

However, they stress that these correlations are material specific and recommend that it is better to establish correlations between CIV and CBR for individual material types rather than rely on generalised correlations.

This section summarises research to determine an equation to relate CBR and CIV for Welsh slate Type 1 aggregate. The data is compared to a good quality Carboniferous limestone Type 1 aggregate.

3.1 THE CLEGG IMPACT SOIL TESTER

The Clegg Impact Soil Tester provides a quick simple means for assessing the compaction of unbound materials such as aggregate and soils. The 4.5kg Hammer Tester contains an accelerometer which measures deceleration when dropped from a fixed height.

The peak deceleration of the hammer relates to the bearing strength and stiffness of the material with the value attained after the forth drop recorded as the Impact Value.

3.2 LABORATORY INVESTIGATION

Laboratory testing compared CBR and CIV of Type 1 Welsh slate and carboniferous limestone aggregate prepared at a range of wet density, moisture content and compaction conditions.

The test specimens were compacted in a 150mm diameter steel mould using a 750W vibrating hammer mounted in a frame weighted to provide a load of 0.4kN on the vibrating plate.

The energy transferred to the material was 10 Joules per blow with an average blow rate of 30 blows per second. The resultant rate of compactive effort was calculated to be 68kJm^{-3}s^{-1}.

The test specimens were prepared at moisture contents ranging from 0 to 6% and represents material used on-site. The wet density of each test specimen was calculated after compaction by measuring change in volume of the compacted material contained within the cylindrical steel mould.

Compaction was stopped every 30 seconds to measure CIV and specimen height. Ten Impact Values were recorded at each interval. However, as recommended in the literature, the impact value recorded after the 4th impact was used in subsequent data analysis.

CBR was determined on test specimens prepared and compacted using the same procedure. The test method followed the principles of the standard method and CBR was determined after 15, 30, 60, 240 and 640 seconds compaction using the Force/Penetration curve set out in BS EN 13286-47: 2004.

Wet density was measured using the volumetric method, which allowed CBR to be correlated with CIV for slate at the range of moisture contents.

3.3 ANALYSIS OF CIV AND CBR DATA

Figure 3.1 plots the 4th CIV against wet density for both the slate and limestone aggregates at moisture contents ranging from 0 to 6%. Power regression trend lines have been plotted through the data and the R-squared value shown.

This shows very good correlation between wet density and Clegg. It clearly shows that the Clegg apparatus gives a lower Impact Value result for slate than for limestone. For example, a wet density of 2000 kgm^{-3} would have a Clegg value of approximately 25 for slate and 35 for limestone.

Figure 3.2 shows power regression trend lines for the slate aggregate at moisture contents of 0, 2, 3 and 4%. This shows very good correlation between wet density and Clegg.

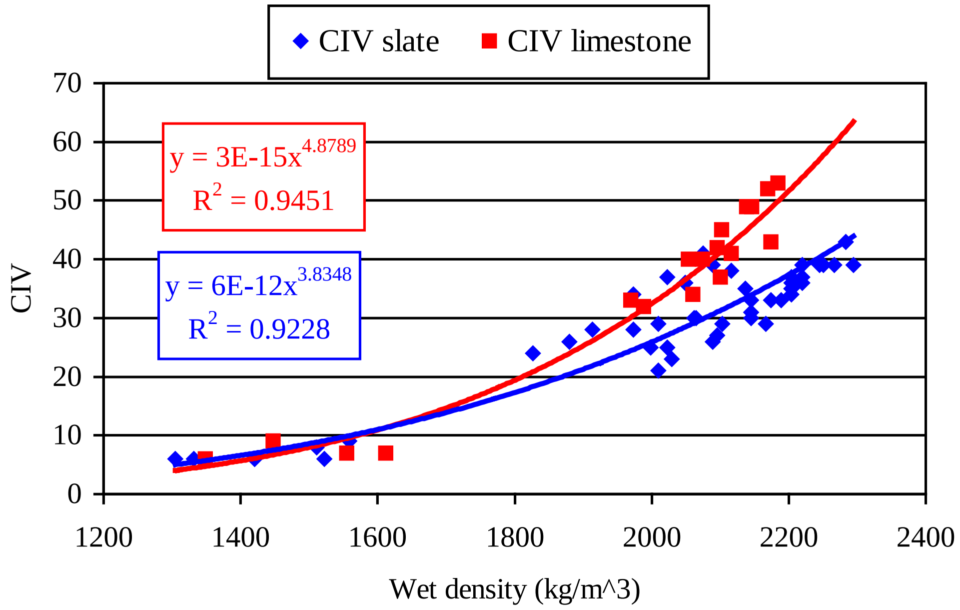


Figure 3.1 Wet density v. CIV for slate and limestone

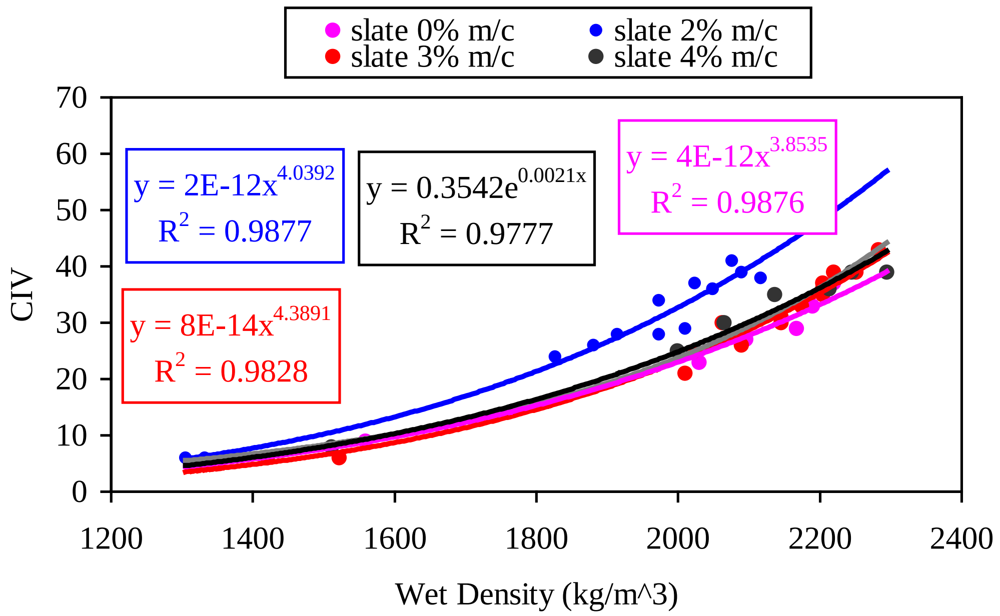


Figure 3.2 Wet density v. CIV for slate at 0, 2, 3 and 4% moisture content

A series of tests were carried out to determine the CBR of laboratory prepared slate samples at 2%, 3% and 4% moisture content. Figure 3.3 shows the relationship between CBR and wet density.

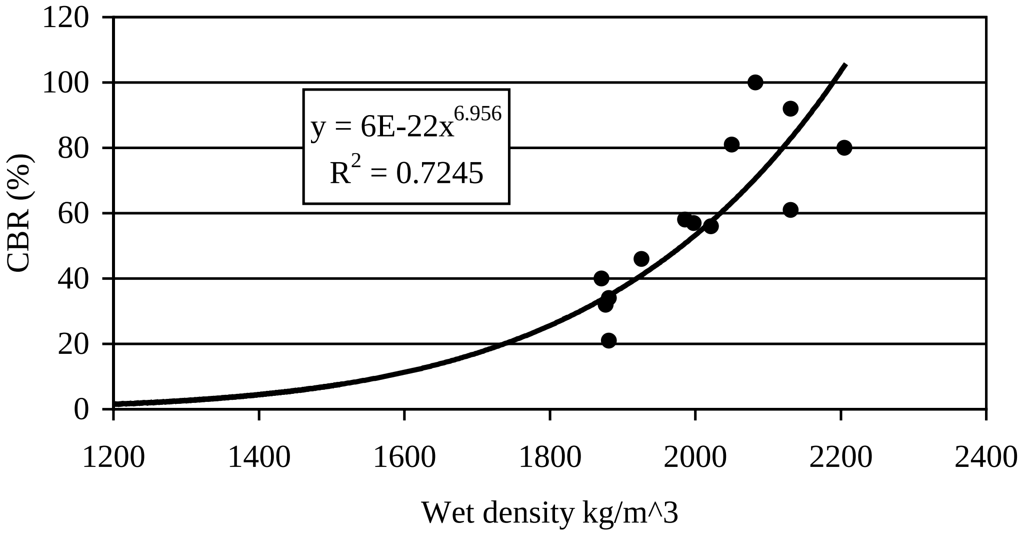


Figure 3.3 Plot of wet density and CBR for slate

3.4 CALCULATION OF A LABORATORY SLATE CIV CBR CORRELATION EQUATION

Reported CBR-CIV relationships typically take the form of a power regression such as those shown in Figures 3.1, 3.2 and 3.3. In order to determine a laboratory CBR-CIV relationship for slate Type 1, the regression equations from Figure 3.1 and 3.3 were combined to give the following regression equation for slate Type 1 aggregate:

CIV = 6E – 12 x Wet Density $^{3.8348}$ $R^2 = 0.9226$

CBR = 6E – 22 x Wet Density $^{6.956}$ $R^2 = 0.7245$

CBR = 0.1360 (CIV)$^{1.814}$

4.0 IN-SITU COMPACTION TRIALS FOR WELSH TYPE 1 SLATE AGGREGATE

This section summarises the findings of compaction trials conducted in North Wales using slate as Type 1 sub-base material. Two types of application were considered i.e. typical new road construction and trench reinstatement.

The aim was to provide field data relating CIV to wet density and Equivalent %CBR at different stages of compaction using a range of compaction equipment. This has shown slate with low CIV to be well compacted with high Equivalent %CBR.

4.1 DESCRIPTION OF TRIAL SITES

The first trial site was located at Llangefni, Anglesey. This was a section of new single carriageway where slate was being used as Type 1 sub-base material for construction of the road foundation and footway.

The slate was being compacted in 150mm thick layers in the carriageway using a vibrating tandem roller and in 100mm thick layers in the footway using a vibrating plate.

The second trial site was located within Penrhyn Quarry, Gwynedd. This trial simulated the use of slate as Type 1 material in both road sub-base and trench reinstatement applications.

A range of vibrating plate and rammer compaction equipment supplied by Wacker GB Ltd. was used to compact the material into 150mm thick layers.

4.2 COMPACTION EQUIPMENT USED

Three different types of compaction equipment were used in the trials. They consisted of:

- 3 tonne Benford vibrating tandem roller.
- 154kg Wacker vibrating plate.
- 4 different models of 2-cycle Wacker vibratory rammer.

4.3 TEST EQUIPMENT USED

Three pieces of test equipment were used onsite. The Clegg Impact Soil Tester was used to take multiple readings of CIV at compaction intervals, on different layers and after compaction by different pieces of equipment.

A Nuclear Density Meter (NDM) was used to measure wet density and moisture content of the material at each compaction interval, on different layers and after compaction by the different pieces of equipment.

Sand Replacement testing was carried out on compacted layers to verify the NDM density measurements. The slate was sampled for laboratory verification of grading analysis and moisture content.

Table 4.1 Test details from Anglesey trial site

Area / Loc.	Layer	Number of roller passes	Comment on visual appearance of slate surface	CIV	Bulk density (Mg/m^3)	M/C (%)
1 / 1	1	0	-	5	1.566	1.6
1 / 2		0	Coarse grading	10	1.961	2.0
1 / 3		0	-	7	1.638	2.1
1 / 4		0	-	5	1.599	1.9
1 / 1		2	Coarse grading	11	1.906	2.0
1 / 2		2	Fine grading	14	2.093	2.3
1 / 1		6	Coarse grading	10	1.987	1.8
1 / 2		6	Fine grading	17	2.117	2.4
2	2	10	Fine	19	2.188	1.4
3 / 1a	1	4	>150mm layer	10	1.992	1.7
3 / 1b		8	>150mm layer	21	2.109	1.7
3 / 1c	2	12	<100mm layer	16	2.191	1.7
3 / 1d		10	<100mm layer	15	1.977	1.4
Footway	-	Compacted	-	25	2.039	3.5

4.4 ANGLESEY TRIAL DATA

The Anglesey compaction trial was carried out during actual construction of the carriageway. Although it was possible to measure CIV and wet density on several layers and at a range of compaction intervals it was difficult to control the amount of compactive effort between measurement intervals due to ongoing construction.

Testing was carried out at 4 areas within the site i.e. three in the carriageway with the fourth in the footway. At each area between 1 and 4 test locations (approx. $1m^2$ each) were assessed using NDM and CIV.

These locations and areas were representative of compaction conditions that varied from loose material to material which received a total of 10 roller passes. At each test location the bulk density was first determined using the NDM (BS 1377, 1990).

A series of 6 CIV tests were then carried out in accordance with the site test procedure given in the Clegg operations manual (Deakin, 2001). The mean 4th impact value was reported as the CIV for each test location.

A summary of the test data for the Anglesey site is given in Table 4.1. The bulk density determined by NDM was corrected using Sand Replacement test data carried out in area 2 (BS 1377, 1990).

NDM determined moisture content data was verified using samples of slate oven-dried in the laboratory. The values reported in Table 4.1 have been corrected.

4.5 PENRHYN QUARRY TRIAL DATA

The compaction trial at Penrhyn Quarry was planned to gather in-situ CIV and bulk density data under more controlled conditions than the Llangefni site. The guidelines set out in ASTM D 5874-95 (ASTM, 1995) were followed.

This recommends preparing test strips of uniform layer thickness and testing after 2, 4, 8 and 16 passes of the compaction equipment.

Table 4.2 details the compaction equipment used at the Penrhyn Quarry site. These were supplied and operated by Wacker GB Ltd. They consisted of a vibrating plate and 3 types of rammer typical of compaction equipment used for trench reinstatement.

Two conditions were assessed:

- The first was an open ground 5 x 3m area, where Type 1 slate aggregate was compacted in 2 layers of 150mm compacted thickness.
- The second was a 5 x 1m trench reinstated with a single layer of 150mm compacted thickness.

The trench and open ground areas were both divided into three equal strips. Each strip was compacted with a different piece of equipment.

Table 4.2 Compaction equipment used at Penrhyn Quarry trial site

Trial area / section	Equipment	Impact energy (J)	Shoe size (mm)
Open ground 1	Variable strike rammer BS65V	79	280x330
Open ground 2	Fixed rammer BS602i	85	280x330
Open ground 3	Vibrating plate DPU25/40H	-	400x400
Trench strip 1	Fixed rammer BS52Y	-	170x330
Trench strip 2	Fixed rammer BS602i	85	280x330
Trench strip 3	Fixed rammerBS502	76	250x330

At each test interval bulk density and moisture content were determined using a NDM. CIV was determined as the average 4th impact value at 3 impact test locations.

The NDM bulk density results were corrected using sand replacement data and moisture contents verified using oven-dried slate samples collected on-site. Table 4.3 gives the mean 4th CIV, bulk density and moisture content at the open ground trial area for each layer, strip and an estimate for the amount of compactive effort.

Table 4.3 gives the mean 4th CIV, bulk density and moisture content at the trench trial area for each strip and an estimate of compactive effort.

Table 4.3 Penrhyn Quarry test data - open ground trial

Layer	Strip	Number of passes	Compactive effort (kJ/m^3)	CIV	Bulk density (Mg/m^3)	M/C (%)
1	1	2	194	12	1.956	1.7
		4	388	15	2.053	2.0
		8	776	15	2.078	2.1
		16	1552	18	2.145	2.5
	2	2	194	12	1.968	1.4
		4	388	13	2.051	1.5
		6	582	15	2.074	3.1
		8	776	15	2.068	2.0
		16	1552	20	2.142	3.1
	3	1	-	7	1.843	2.1
		2	-	8	1.939	2.0
		4	-	9	1.922	2.7
		6	-	11	1.922	2.1
		8	-	10	2.043	1.6
		12	-	14	2.056	1.8
2	1	0	0	5	1.692	3.3
		2	194	10	1.995	3.2
		4	388	15	2.096	3.3
		8	776	14	2.249	3.3
		16	1552	18	2.417	3.5
	2	2	194	10	1.963	3.1
		4	388	15	2.148	3.0
		8	776	15	2.324	3.2
		16	1552	22	2.457	3.5
	3	2	-	10	1.907	4.0
		4	-	13	2.029	3.2
		8	-	11	2.262	3.1
		16	-	14	2.314	3.5

Table 4.4 Penrhyn Quarry test data - trench reinstatement trial

Strip	Passes	Compactive effort (kJ/m^3)	CIV	Bulk density (Mg/m^3)	M/C (%)
1	0	0	5	1.716	2.5
	2	-	11	1.934	2.3
	4	-	15	2.032	1.9
	8	-	17	2.098	2.2
	16	-	19	2.186	2.4
2	2	194	12	2.087	3.0
	4	388	15	2.130	3.1
	6	582	12	2.202	4.0
	8	776	19	2.236	5.2
	16	1552	22	2.350	4.6
3	2	142	15	2.107	4.1
	4	284	13	2.242	4.2
	6	426	15	2.257	5.1
	8	569	16	2.358	4.6
	16	1137	21	2.424	8.2

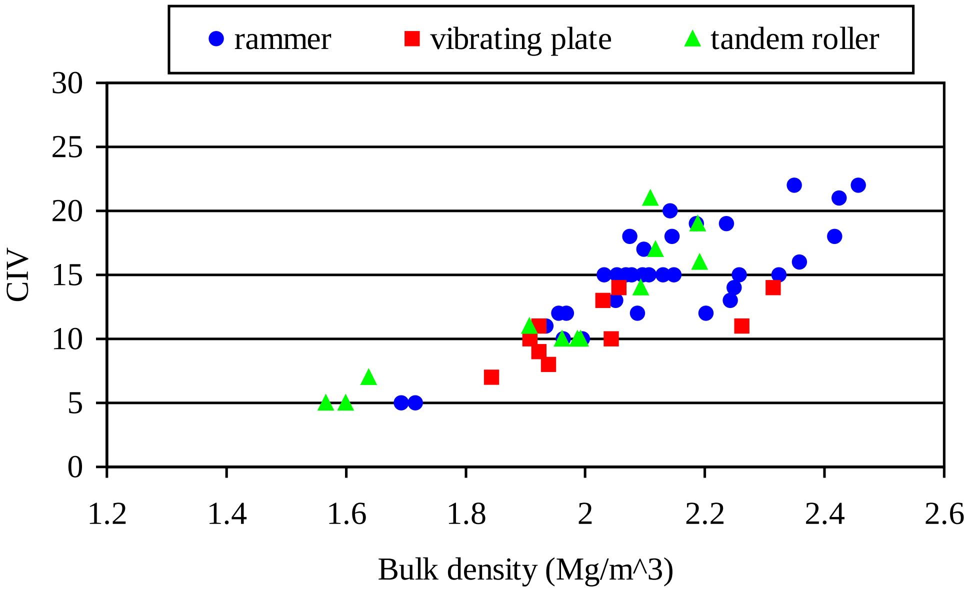


Figure 4.1 Plot of bulk density and 4th reading CIV data for different methods of on-site compaction

4.6 ANALYSIS OF TRIAL SITE DATA

Figure 4.1 plots the bulk density and 4th reading CIV data for the three types of compaction equipment used in the Penrhyn Quarry and Llangefni site trials. The data plots as expected i.e. an increase in bulk density corresponds to a general increase in CIV.

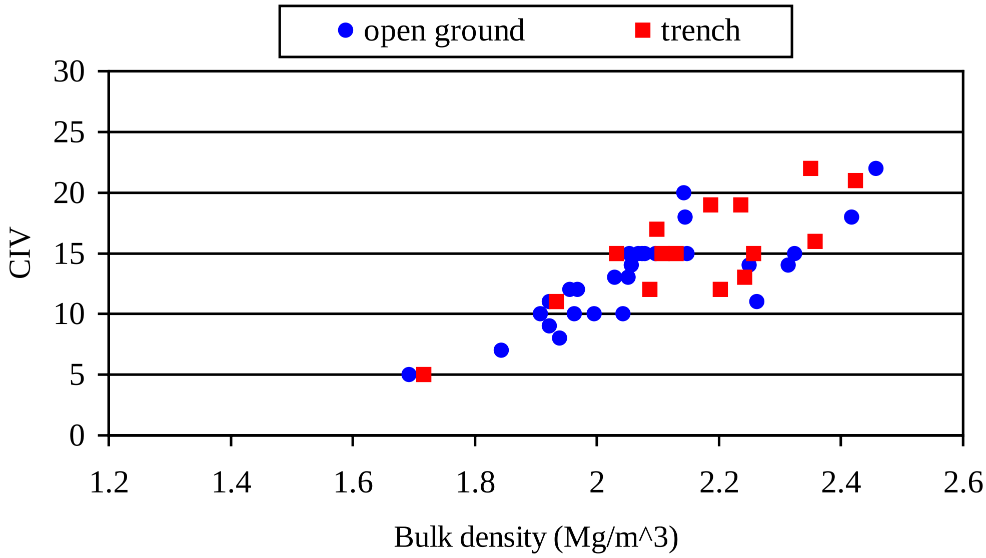


Figure 4.2 Plot of bulk density and 4th reading CIV data for open ground and trench conditions

Figure 4.2 plots bulk density and CIV for both the open ground and trench conditions. This shows the two sets of data to plot within the same overall trend.

It should be noted that the Penrhyn Quarry trial was conducted over a 2-day period. The first day was dry. However, it started to rain on the morning of the second day, as the open ground trial was finishing. Heavy rain caused the moisture content of the trench reinstatement to increase as the trial progressed.

The effect of high moisture contents on the test data due to heavy rain during the reinstatement trial must be recognised. Table 4.4 shows that some of the slate used in the Penrhyn Quarry trial had been compacted at moisture contents up to 8%.

4.7 CORRELATION OF ON-SITE CIV – WET DENSITY DATA

Figure 4.3 plots the CIV – Wet Density slate data determined during on-site testing. A power regression trend line has been plotted through the data and the R-squared value shown.

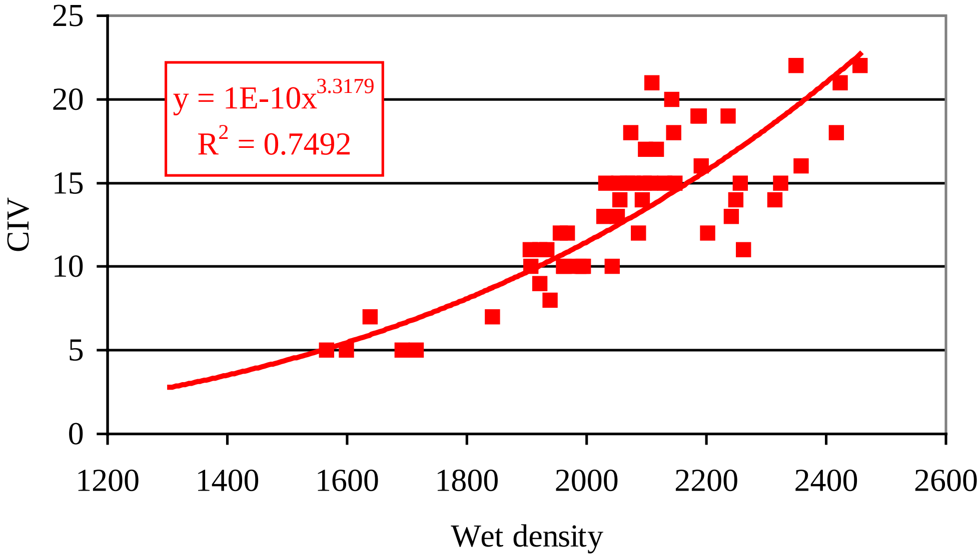


Figure 4.3 CIV – Wet Density plot for site data

The following correlation was determined:

Site data CIV = 1E – 10 x Wet Density$^{3.3179}$

This shows the trend for the site trial data to be different from the laboratory determined data i.e. for a given wet density, the corresponding Clegg value obtained on-site will be lower than that predicted in the laboratory.

For example, a wet density of 2000 kgm^{-3} would correspond to a CIV of approximately 36 in the laboratory and 12 on-site. This highlights a number of issues.

For example, the ability to predict on-site performance based on laboratory testing, or more importantly, reliance on a CIV specification that is assumed to be applicable to all materials.

4.8 CALCULATION OF AN ONSITE CIV – LABORATORY EQUIVALENT CBR CORRELATION EQUATION

The correlations determined using laboratory and onsite data were integrated to determine the following power regression equation relating CIV with Equivalent CBR:

$$\text{Equivalent CBR} = 0.1538\ (\text{CIV})^{2.3769}$$

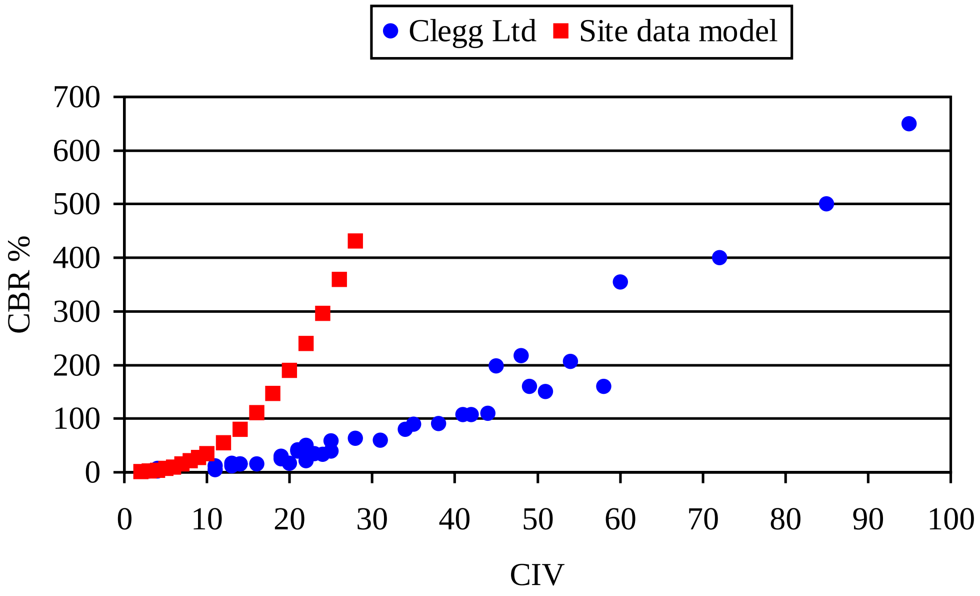


Figure 4.4 Comparison of slate site Equivalent CBR – CIV model with data supplied by Clegg Ltd

Figure 4.4 compares predicted values of Equivalent CBR using this model with data provided by Clegg Ltd. The plot shows rapid increase in Equivalent % CBR with CIV indicating that onsite, slate quickly compacts, gains density and load bearing properties.

4.9 CONVERSION TABLES

A conversion table is given in Table 4.5 for the commonly used Clegg (1980) and new slate equation. This reflects the rapid gain in performance with small increases in CIV for compacted slate

Table 4.5 Conversion table relating Clegg data with equivalent % CBR based on Clegg (1980) and slate power model

	Equivalent % CBR	
Clegg Impact Value	Clegg (1980)	Slate power model
0	0	0
1	0	0
2	0	1
3	1	2
4	1	4
5	2	7
6	3	10
7	3	15
8	4	21
9	6	27
10	7	35
12	10	55
14	14	80
16	18	111
18	23	147
20	28	190
22	34	240
24	40	296
26	47	360
28	55	431
30	63	510
32	72	596
34	81	691
36	91	794
38	101	906

5.0 CONCLUSIONS

The research reported in this report has found that Type 1 unbound slate aggregate does not appear to perform in a manner similar to conventional unbound materials.

The unique flaky shape characteristics of slate positively affect its performance as unbound aggregate i.e. most notably compaction, deformation and load bearing properties.

This has been confirmed in both the laboratory and on-site trials.

5.1 MAIN FINDINGS OF THE LABORATORY INVESTIGATION

The main conclusions from the laboratory investigations are summarised as follows:

- Slate can meet the property requirements specified for unbound use in highway construction. Indeed, it could be suitable for use in asphalt layers.

- Despite this evidence and successful local use in road construction projects in North Wales, slate is still viewed as being inferior because of its shape.

- This research considered a range of testing regimes using gyratory and Marshal compaction to investigate its performance. It has been shown that there are predictable relationships between moisture content, grading and density. The slate was not particularly difficult to compact.

- Whilst some flaky particles broke during compaction, they did not re-orientate to form layers or make the unbound layer any more difficult to compact.

- The type of compaction i.e. kneading versus impact also appears to have an effect. It is suggested that this may have an influence on impact types of testing being carried out as part of a quality control process on-site.

- A wheel-tracking test showed that flaky slate performed identical to the best basalt in Northern Ireland in terms of resistance to permanent deformation.

- Compared to the limestone Type 1 aggregate assessed, slate was found to have a greater wet density at a specific CIV. As density is a function of compaction, slate Type 1 aggregate will have a lower CIV than limestone after a similar amount of compaction.

- Laboratory investigation has determined a CBR – CIV correlation for slate Type 1 aggregate. Comparison with published research findings for other unbound materials confirms that CIV underestimates CBR.

5.2 MAIN FINDINGS OF THE FIELD TRIALS

The field trials have provided valuable insight into how Type 1 slate material compacts in-situ using different compaction techniques, moisture contents and site conditions. The main conclusions from the field trials are summarised as follows.

- The two sites provide data which covers the two highway applications for Type 1 material i.e. road sub-base and trench reinstatement.

- The tandem roller and rammer compact the slate to achieve significantly higher bearing strength than the vibrating plate.

- The difference in compaction densities between open ground and trench reinstatement may be more indicative of the higher moisture contents of >4% in the trench (due to heavy rainfall during the last period of testing) rather than trench wall containment.

- Significant correlation was found between bulk density and Clegg Impact Value.

- A 150mm thick compacted layer of Type 1 slate material gives a typical in-situ CIV of approximately 15 after 8 compaction passes.

- CIV of 15 is sufficient to ensure adequate bearing strength and density for slate used as Type 1 aggregate to road base levels in trench reinstatements.

- The following equation was determined to predict Equivalent %CBR based on field determination of Clegg Impact Value:

$$\text{Equivalent \%CBR} = 0.1538\,(\text{CIV})^{2.3769}$$

6.0 REFERENCES

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