Ballast Compaction and Verification for Railway Projects in Ireland

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ABSTRACT:

This paper reviews the standards and engineering practices governing the compaction of railway ballast in Ireland, the United Kingdom, and Germany. Railway ballast is not compacted to a target Proctor density; instead, consolidation is achieved using rail-specific methods such as tamping, regulating, and dynamic track stabilisation (DTS). Across all three jurisdictions, acceptance of ballasted track is performance-based and relies on achieved track geometry, stability, and compliance with infrastructure manager requirements rather than density-based earthworks criteria. The study draws on works on ballasted track [1], Network Rail [2], Irish Rail [3], DB InfraGO[6][7] technical directives and railway ballast performance papers, supplemented by data from the Irish Rail Glounthaune to Midleton Twin Track Project.

Field trials were undertaken to assess the influence of compaction method, applied energy, roller mass, and number of passes on subgrade, capping, and ballast performance. Results confirm that subgrade and capping layers consistently exceeded performance requirements under conventional earthworks compaction. In contrast, ballast performance was highly sensitive to compaction energy. High-mass vibratory and dead-weight rollers produced short-term stiffness gains but caused ballast particle degradation and fines generation, rendering them unsuitable. Controlled low-energy methods, such as pedestrian-operated vibratory plates, achieved compliant stiffness while preserving particle integrity, drainage, and long-term performance.

Keywords: capping, ballast compaction, geosynthetics, railway trackbed, LWD testing, subgrade performance.

1 INTRODUCTION

The paper reviews the specifications and governing standards for railway ballast compaction in Ireland, the United Kingdom, and Germany. It highlights that ballast is not compacted to a Proctor density; instead, consolidation is achieved through tamping, regulating, and, where applicable, dynamic track stabilisation. Acceptance is based on achieved track geometry, stability, and handover criteria rather than conventional earthworks density requirements.

The research is informed by data and practical experience from the Irish Rail Glounthaune to Midleton Twin Track Project, part of the Cork Area Commuter Rail (CACR) programme. The project involves the upgrade of approximately 10 km of railway, including the construction of a second track alongside the existing single line and the installation of new signalling systems, with completion planned for late 2026. The findings directly inform the development and application of railway ballast compaction specifications.

1.1 Ireland

In Ireland, acceptance of ballasted railway track works is governed by (I.S. EN 13231-1:, 2023)[1] which adopts a performance-based approach and does not specify target ballast densities nor conventional earthworks compaction criteria. Under Irish Rail specification (IR-CEE-TRK-SPN-007 V2:, 2020) [2], traditional civil engineering compaction methods are not appropriate for ballast, as ballast performance depends on maintaining an open-graded, angular, low-fines structure with high permeability.

Conventional density measures, such as Proctor density, percentage of maximum dry density, or relative density are therefore not applicable and shall not be specified. High-energy mechanical compaction is prohibited because it accelerates particle breakage, increases fines content, reduces permeability, and compromises long-term track performance. Instead, ballast consolidation is achieved through rail-specific methods such as mechanical tamping and, where required, Dynamic Track Stabilisation (DTS), which promote effective particle rearrangement and interlock without damaging the ballast. Limited, low-energy localised plate compaction may only be permitted with prior written approval.

1.2 United Kingdom

In the United Kingdom, ballast compaction and consolidation are governed by (NR/L2/TRK/2102 Issue 12:, 2023)[3] which regulates ballast compaction for plain line renewals in Track Categories 1A, 1, and 2, permitting consolidation methods such as approved vibrating rollers and plates (subject to defined limits), Dynamic Track Stabilisation (DTS), and, for lower-category track, tamping with ballast placed in thin layers.

Compaction must be sufficient to enable safe line reopening, support permitted operating speeds, and achieve the specified track geometry, with particular emphasis on adequate consolidation of the formation or bottom ballast layer prior to final ballast placement. In practice, tamping remains the primary method for restoring geometry, typically supplemented during construction and renewals by vibrating plates, approved rollers, and DTS.

The standard applies to ballasted track designed for speeds up to 140 mph and covers new construction, renewals, and upgrades. It classifies track from Categories 1A to 6 based on line speed and Equated Million Gross Tonnes Per Annum (EMGTPA), with each category defining ballast depth, formation requirements, allowable consolidation methods, and geometric tolerances, Figure 1.

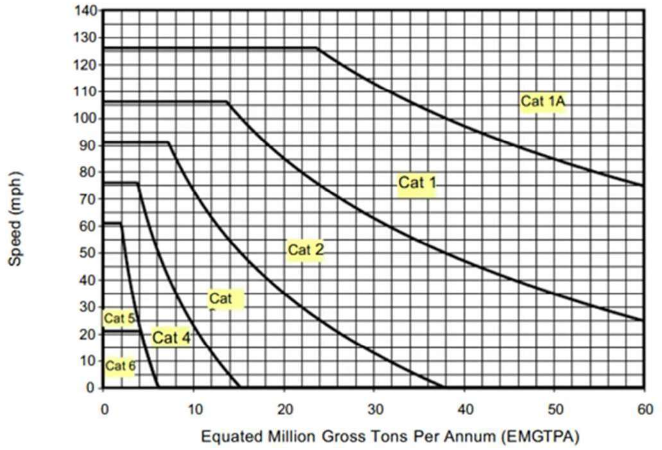


Figure 1: Track Classification

Table 1: summarises the requirements for line speed, excavation depth below ballast, compaction levels, and permitted compaction methods, including vibrating plates, vibrating rollers, and Dynamic Track Stabilisation (DTS).

Table 1: Track Category (TC) and Compaction Summary

TC	Speed Range (mph)	Excavation per 10.3.4	Compaction Requirement	Vibratory Plates	Vibratory Rollers	DTS
1A	≈110–145	Mandatory	Mandatory	✓ (local)	✓✓	✓✓
1	≈70–125	Mandatory	Mandatory	✓	✓✓	✓
2	≈45–110	Mandatory	Mandatory	✓	✓	✓
3	≈35–80	Mandatory	Consider	✓	✓	✓
4	≈25–70	Mandatory	Consider	✓✓	△	△
5	≈10–50	Mandatory	Usually no	✓ (local)	✕	✕
6	≈0–25	Mandatory	No	△	✕	✕

Legend: ✓✓ = typically expected ✓ = permitted
△ = limited/case-by-case ✕ = generally not appropriate

1.2.1 Ballast requirements

Ballast shall consist of new or clean recycled material, with retention of existing ballast permitted only with explicit approval from the Responsible Asset Manager (Track). The ballast must provide vertical and lateral load support, track stability, and rapid drainage. Minimum ballast depths for plain line track (ordinary track without switches or crossings) are typically 300 mm below sleeper level, with reduced depths of 250 mm for Track Categories 1A and 1, and 200 mm for Categories 2 - 6 where no geotextile, grid, or sand blanket is present. During construction, a minimum of 180 mm of ballast is required above any geotextile prior to tamping. Ballast depth is measured from the bottom of steel sleepers or the bottom of the sidewall for concrete sleepers.

Where ballast thickness is 480mm or less, placement in a single layer is permitted; for depths greater than 480mm, ballast shall be placed and compacted in layers not exceeding 300mm. Increasing the number of compaction passes, increases stiffness, reduces early settlement, and improves lateral resistance.

Full-depth excavation and subgrade preparation are required where drainage is inadequate, cess levels are excessive, obstructions are absent, or adjacent lines remain in service, with excavation extending to the six-foot centreline. For Track Categories 1A to 2, the bottom ballast layer must be laser levelled.

Ballast compaction is mandatory for track renewals in Categories 1A to 2 and optional, though recommended, for Categories 3 to 6. Permitted consolidation methods include vibrating rollers, vibrating plates (used in layers for greater depths), Dynamic Track Stabilisation (DTS), and tamping and lifting for lower-category track. The objective is to achieve adequate ballast stiffness and minimise long-term settlement. Where DTS is not used, (NR/L2/TRK/2102 Issue 12:, 2023)[3] (TII, 2024)[4] requires a minimum of three compaction passes for opening speeds up to 60 mph and six passes for speeds above 60 mph.

1.3 Germany

In Germany, railway ballast compaction and consolidation are governed by technical directives issued by DB InfraGO (formerly DB Netz). Geotechnical and track formation requirements for the ballast bed are defined in the Technical Directive 836[5] series; while tamping and lining operations are covered by the Directive 824[6] series. Post-tamping consolidation and stabilisation are the primary ballast compaction mechanisms and are regulated by DS 820 03 15[7], which governs the use of Dynamic Track Stabilisation (DTS) for both plain line and switches (Feurig, 2020)[8].

Acceptance of ballasted track is performance-based and relies on achieved track geometry, stability, and compliance with prescribed construction and maintenance procedures rather than density-based compaction criteria. German practice distinguishes between different stabilisation stages, applying defined parameter sets for each. Directive DS 820 03 15 [7] specifies key operational parameters such as working speed, applied vertical surcharge, and vibration frequency which control pre-settlement, recovery of lateral resistance, and minimisation of damage to ballast and track components.

1.4 *Delft Research*

Shi [9] explained how railway ballast deteriorates under repeated cyclic loading from train traffic. High stress concentrations particularly beneath sleepers cause progressive particle degradation through breakage, fracture, and abrasion. As ballast particles degrade:

- Their angularity and surface roughness decrease.
- Inter-particle friction and mechanical interlock are reduced.
- Overall structural stability of the ballast layer declines.

Particle breakage also produces fine materials that accumulate in ballast voids. This reduces permeability and drainage capacity, leading to water retention and mud pumping, which further weakens mechanical performance. Experimental findings indicate that ballast degradation is a major contributor to track settlement and geometry deterioration. The ballast layer is responsible for most short-term vertical deformation in conventional ballasted railway tracks. Hence, it can be inferred that the over-compaction of the ballast is not acceptable.

2 GLOUNTHAUNE TO MIDELTON EXPERIENCE

The compaction of the railway sub-grade, capping, and ballast has been a subject of ongoing debate. Soft spots were identified at various locations along the project during the compaction of the sub-grade, capping and ballast using a Bomag BW 145 DH-5 (4.8t) vibratory roller. These soft spots were identified by heat maps, highlighted in red and presented in Figure 2.

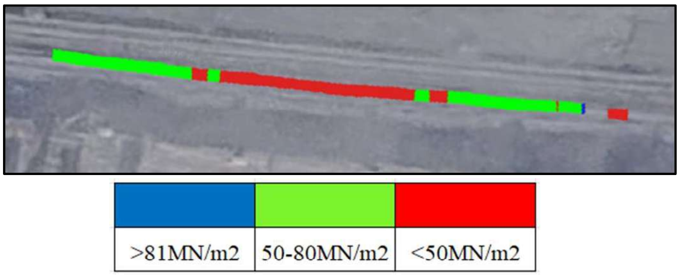


Figure 2: Compaction Heatmap (EV2)

There is some uncertainty about the accuracy of the heat map results. The calibration of the reported compaction efforts has been challenging to verify, which raises questions about the reliability of the data. The use high energy vibratory compaction rollers on ballast also contradicts Irish Rail specifications. Hence the reason for the ballast compaction testing which is considered in Section 4.

3 GLOUNTHAUNE TO MIDELTON WORKS REQUIREMENT

The Works Requirements specify the placement and compaction of the subgrade, capping layer, and ballast within the rail track bed structure. The ballast consisted of clean, angular crushed stone, placed and compacted to achieve optimum particle interlock and stiffness, avoiding excessive particle degradation and reduction in drainage performance.

3.1 *Sub-Grade Requirements:*

- Topsoil and organic material were stripped from areas to receive permanent works.
- Where subgrade materials were unsuitable, they were treated with lime or hydraulic binders or were excavated and replaced.
- Geotextiles or geogrids were installed where required by the design to provide separation or reinforcement when CBR values were < 2%.
- The prepared subgrade achieved a minimum CBR of 5%.
- Where plate load testing is required, the Ev2 modulus shall not be less than 30 MN/m² - 45mN/m3 as per the Midelton Twin Track Project (GMTT) Appendix 6/7.
- Layer thickness and compaction effort did comply with the limits specified for the relevant material Class.

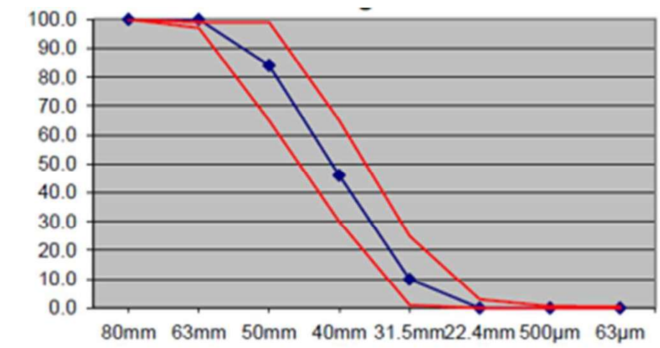
3.2 *Capping Layer Requirements:*

Class 6F1 capping was placed and compacted in accordance with method 2 of (TII, 2024) CC-SPW-00600 [4].
Table 6/4, GMTT Appendix 6/7.
Required stiffness: Ev2 ≥ 60 - 90 MN/m2, CBR > 15%.

3.3 *Ballast*

Railway ballast is a key structural and drainage layer that distributes wheel loads, controls settlement, and protects the subgrade. Its performance depends on particle angularity, interlock, and confinement rather than density-based compaction. The open-graded structure provides track restraint, supports rail stability, allows effective drainage, and reduces the risk of pumping and frost damage.

Ballast also helps dissipate dynamic loads, enables maintenance through tamping and realignment, and acts as a replaceable sacrificial layer above the formation. It should be placed mechanically in a uniform single lift, typically 300–500 mm thick, without wetting or moisture conditioning. Ballast grading should comply with I.S. EN 13450, Grading Category D, including the relevant Irish Rail grading envelopes for 31.5–50 mm and 31.5–63 mm materials, Figure 3.



Test	Result	Specification
Flakiness Index	15	0-35
Particle Length	<4	4

Figure 3: Ballast Grading

3.3.1 Compaction Control:

Restrictions on high-energy vibration and compaction are justified by evidence that excessive mechanical loading accelerates ballast particle breakage, increases fines content, and degrades drainage and long-term performance. Ballast consolidation is therefore achieved using rail-specific methods. Approved mechanical tamping is used to restore particle interlock and track geometry, typically requiring 3-5 tamping cycles depending on stiffness requirements, followed by Dynamic Track Stabilisation (DTS) to simulate train loading, pre-settle the ballast, and stabilise the track bed. Research confirms that ballast degradation during maintenance is governed by contact forces generated during mechanical consolidation, with synthesis studies (Shi, 2023)[9] demonstrating that maintenance activities increase fines content and reduce ballast service life. Consequently, static or vibratory roller compaction is not permitted for ballast.

Ballast stiffness is verified using Plate Load Testing, with an Ev2 modulus range of 50-80 MN/m2. A lower bound around 50 MN/m² typically relates to ensuring adequate structural support and rider stability. An upper bound such as 80 MN/m² may be used to avoid over-compaction, crushing of aggregate, or excessively ballast stiffness that could results in differential settlement issues.

4 CASE STUDIES

4.1 First Test -02.07.2025.

Two side-by-side test bed sections were constructed to allow comparative assessment of compaction performance. Each test bed was approximately 20 m long and 3 m wide and simulated a railway track bed constructed on a firm subgrade with a CBR exceeding 60%, representative of the existing track formation conditions. Both test beds comprised of a 250 mm thick 6F2 capping layer placed on the subgrade. Test Bed 1 was compacted using a BOMAG BW 100 AD-5, (2.5t vibratory roller) Figure 6; while Test Bed 2 was compacted using a BOMAG BW 213 D-5, (12.5t vibratory roller), Figure 4. The stiffness of the compacted capping was measured using a Lightweight Deflectometer (LWD).

A 300 mm thick ballast layer was subsequently placed on the capping and compacted using the same equipment. LWD testing was repeated following ballast placement and compaction to assess the resulting track bed stiffness. The test results, including stiffness values and number of compactions passes for both the capping and ballast layers, are summarised in Table 2.

Figure 4: BOMAG BW 213-D-5 on test bed 2

Table 2: Test Beds Results 02.07.2025

Test Bed	Description	Evd (MN/m2)	EV2 (MN/m2)	CBR%
	Sub-Grade	115.4	230.8	>60
1	Capping 4 passes 2.5t vibrator	61.1	122>50-90	>60
1	Capping 4 passes 2.5t vibrator	59.5	119>50-90	>60
1	Ballast 4 passes 2.5t vibrator	39.1	78≈50-80	29.34
1	Ballast 4 passes 2.5t vibrator	32.6	65≈50-80	22.70
2	Capping 2 passes 12.5t vibrator	34.4	69≈50-90	24.44
2	Capping 2 passes 12.5t vibrator	41.0	82≈50-90	31.50
2	Capping 4 passes 12.5t vibrator	24.8	49<50-90	15.0
2	Capping 4 passes 12.5Tvibrator	22.2	44<50-90	13.99
2	Ballast 4 passes 12.5t vibrator	30.3	61≈50-80	20.57
2	Ballast 4 passes 12.5t vibrator	24.8	50≈50-80	15.86

4.2 BOMAG BW 213 D-5

The BOMAG BW 213 D-5 is a heavy, single-drum vibratory roller (12.5-16t class) designed for high-energy soil compaction. It features a 2.13 m wide drum, operates at approximately 36 Hz with a nominal amplitude of 1.9 mm, delivering compaction energy suited to heavy earthworks. The machine incorporates an intelligent compaction system that displays colour-coded heat maps indicating relative stiffness levels. During trial testing, however, significant limitations were identified. The applied compaction effort could not be reliably calibrated or independently verified using Lightweight Deflectometer or plate load testing. In addition, compaction data could not be retained or downloaded when vibration was disengaged or during dead-rolling, thus limiting its suitability for quality assurance and reporting. Visual observations during testing also indicated significant ballast particle breakage under the high compaction energy applied by the BW 213 D-5, Figure 5.

Figure 5: Ballast Particle Damage

4.3 BOMAG BW 100 AD-5

The second compaction plant assessed was the BOMAG BW 100 AD-5, a light articulated tandem roller (approx. 2.5t) with a 1.0 m working width. It is equipped with intelligent vibration control, operates at speeds of up to 10 km/h, and delivers a centrifugal force of approximately 30-34 kN, Figure 6

4.4 Second Test - 13.07.2025

The setup was repeated for the second test. The results for the capping and ballast layers are summarised in Table 3.

Figure 6: BOMAG BW 100AD-5 on test bed 1

Table 3: Test Bed Results 13.07.2025

Test Bed	Description	Evd (MN/m2)	EV2 (Mn/m2)	CBR%
	Sub-Grade	113.1	226	>60
1	Capping 2 passes 2.5t dead	40.1	80≈50-90	30≈15-37
1	Capping 2 passes 2.5t dead	36.9	74≈50-90	27≈15-37
1	Ballast 4 passes 2.5t dead	27.0	54≈50-80	18≈15-30
1	Ballast 4 passes 2.5t dead	30.1	60≈50-80	20≈15-30
2	Capping 2 passes 12.5t dead	37.3	74≈50-90	27≈15-37
2	Capping 2 passes 12.5t dead	35.5	71≈50-90	26>15-37
2	Ballast 2 passes 12.5t dead	22.0	44<50-80	14<15-30
2	Ballast 2 passes 12.5t dead	21.3	43<50-80	13<15-30
2	Ballast 2 passes 12.5t dead	22.9	46<50-80	14<15-30
2	Ballast 2 passes 12.5t dead	23.5	47<50-80	15≈15-30
2	Ballast 4 passes 12.5t dead	26.9	54≈50-80	18≈15-30
2	Ballast 4 passes 12.5t dead	29.5	59≈50-80	20≈15-30
2	Ballast 2 passes 12.5t vibrator	38.7	78≈50-80	29≈15-30
2	Ballast 2 passes 12.5t vibrator	32.5	65≈50-80	23≈15-30

5 WACKER PLATE TESTING

For completeness, a walk behind Wacker plate test was carried out on the compaction of the ballast on 04.02.2026, Table 4.

5.1 Conversion of EV to CBR

The following results show the conversion of elastic modulus values (EV) to California Bearing Ratio (CBR) using the equation: (Carter, 2016) [10]

$$Ev = 3.6 \cdot CBR - 0.088 \cdot CBR^{1.73} + 3 \quad (1)$$

Because the equation cannot be rearranged explicitly, the CBR values were obtained using an iterative numerical solution (Newton–Raphson method).

Table 4: Wacker Plate Test Results

Ev2 (MN/m2)	CBR %	Modulus Target (MN/m2)	Number of Passes
64	22.13	50-80	4
52	16.85	50-80	4
58	19.41	50-80	4

6 LIGHTWEIGHT DEFLECTOMETER

The test simulates the loading effect of a moving vehicle by applying a short-duration load pulse equivalent to a 10-tonne axle travelling at approximately 80 km/h. A 300 mm diameter steel plate is placed on the surface, and a 10 kg mass is dropped from 720 mm, producing a peak contact pressure of about 100 kPa with a load pulse duration of approximately 17 ms. An accelerometer mounted on the plate records the response, and velocity and displacement are derived through signal integration. These measurements are used to calculate key parameters, including the dynamic (resilient) modulus (Evd), bearing capacity, dynamic spring stiffness (Kvd), and compaction quality indicators for construction control.

7 PLATE LOAD TESTS ON BALLAST

After the ballast was compacted using 2.5t roller, plate load testing was carried out in accordance with BS 1377-9 using a 450mm diameter plate. The results are shown in Table 5.

Table 5: Plate load testing of ballast

Test 1	MN/m2	Target MN/m2	Measured CBR % on Ballast
1	97.5	50 - 80	42
2	113.0	50 - 80	58
3	117.6	50 - 80	69
4	102.10	50 - 80	46
5	96.3	50 - 80	41

8 DISCUSSION

The purpose of this research was to identify the optimum compaction method for ballast. High-energy static or vibratory roller compaction applies concentrated contact stresses to angular ballast particles and can accelerate particle breakage and the generation of fines. This is incompatible with the functional requirements of railway ballast, particularly drainage, durability and long-term settlement performance, and is therefore generally prohibited.

The compaction trials demonstrate that track bed performance was strongly influenced by compaction method, roller mass and applied energy. The subgrade consistently provided a very stiff foundation, with EV2 values of approximately 226–231 MN/m² and CBR >60% and was therefore not the controlling layer. The capping layer generally performed satisfactorily, achieving values within the specified range of 50–90 MN/m² and 15–37% CBR, although some variability was observed, likely due to local material condition, moisture content, overworking or test location effects.

Ballast performance was more sensitive to the compaction method. Two static passes with the 12.5 t dead roller produced EV2 values of only 43–47 MN/m², equivalent to approximately 13–15% CBR, which is below or marginal to the required ballast range of 50–80 MN/m² or 15–30% CBR. Increasing to four static passes improved the ballast response to approximately 54–60 MN/m², equivalent to 18–20% CBR, which satisfied the required stiffness range. However, use of the 12.5 t roller, whether static or vibratory, was associated with visible ballast particle degradation. This is not acceptable under Irish Rail requirements, irrespective of the measured stiffness achieved.

Although vibratory compaction produced higher ballast stiffness values, typically 65–78 MN/m² or 23–29% CBR, vibratory compaction is not acceptable for ballast where Irish Rail requirements apply because of the risk of particle breakdown, reduced drainage capacity, fouling and long-term settlement. In addition, the 12.5 t roller's heat map and recording system does not operate when vibration is switched off, limiting its value for quality assurance when used in static mode.

Plate load testing of ballast compacted using the 2.5 t roller produced modulus values of approximately 96–118 MN/m², with CBR values of 41–69%. These values exceed the specified ballast acceptance range of 50–80 MN/m² and 15–30% CBR. While the results confirm that the ballast was not under-compacted, the elevated stiffness may indicate over-compaction, excessive particle interlock, confinement effects or influence from the stiff underlying layers. Such high stiffness values should therefore be reviewed in the context of drainage performance, ballast degradation and long-term settlement risk.

In contrast, Wacker plate compaction achieved inferred CBR values of approximately 17–22%, corresponding to modulus values within the specified 50–80 MN/m² range, without evidence of ballast degradation. This indicates that controlled, low-energy localised compaction can achieve the required ballast stiffness while preserving particle integrity and drainage function.

Overall, the trials indicate that compliant ballast performance is achieved through controlled low-energy consolidation, rather than high-energy densification. Heavy static and vibratory roller compaction should not be adopted where it causes ballast degradation or produces stiffness values outside the specified acceptance range.

9 CONCLUSIONS

The compaction trials demonstrate that trackbed performance is governed primarily by compaction method and applied energy. The subgrade and capping layers generally exceeded the minimum performance requirements and did not control the overall behaviour.

Ballast performance proved highly sensitive to compaction approach. Heavy roller compaction, particularly using the 12.5t roller, caused unacceptable particle degradation and is therefore non-compliant with Irish Rail requirements, irrespective of achieved stiffness. The 2.5 t roller also produced modulus values of approximately 96–118 MN/m², which exceed the specified ballast acceptance range of 50–80 MN/m² and may indicate over-compaction.

Wacker plate compaction with four passes was the only method that achieved ballast stiffness within the specified 50–80 MN/m² range while preserving particle integrity. The findings demonstrate that compliant performance is achieved through controlled, low-energy consolidation, rather than high-energy densification. This approach is aligned with the principles of Network Rail NR/L2/TRK/2102[3], which seek to preserve ballast function and avoid particle degradation.

Under the trial conditions, Wacker plate compaction was the only method that satisfied both the required stiffness criteria and material integrity requirements. The results therefore support the use of controlled low-energy compaction as the preferred method for ballast consolidation, subject to approval by the Infrastructure Owner and verification through appropriate field testing.

These findings may provide a practical pathway for addressing ballast compaction issues. Further research is recommended to confirm repeatability under varying site conditions, refine the method, and optimise ballast performance while maintaining drainage capacity and long-term settlement resistance.

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