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Review

Railway ballast material selection and evaluation: A review

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ABSTRACT

The properties of railway ballast material are affected by the local geologies and climatic environments from which the parent rock is sourced. These factors can make it challenging to select the most appropriate material for railway applications. To address this issue, this paper first reviews the means of ballast selection in complex environments across the world. The selection criteria for ballast materials are compared and test methods for ballast quality quantification are summarised. Next, ballast parent rock types and the implications of mining approaches are discussed, before analysing ballast morphology with respect to ballast size and shape. Then ballast petrography is reviewed with a focus on the effect of mineral composition on performance. Finally, some promising future ballast technologies are discussed with a focus on environmental performance. These include recycled ballast, asphaltic materials, steel slag and ballast gluing. The review shows that regarding ballast selection means and criteria, the number and type of quantitative indicators varies greatly between countries. In particular there are divergences in test methods and quantitative indicators for ballast quality considering material types and local geologies. Suggested future research directions are proposed, such as the effect of tamping and dynamic track stabilisation on ballast properties.

1. Introduction

The terminology ‘ballast’ was originally derived from the ballast used on ships. It was the crushed stone and gravel used for counterweighting British coal ships on their return voyage. These stones and gravel materials were laid upon subgrade on railway coal lines after being removed from the ships. Ballast was later laid on top of the subgrade, afterwards it became an important component of ballasted track.

Ballast is generally defined as a volume of graded crushed rocks, however many other materials have been used or developed to serve as ballast [1]. It is typically laid in a compacted layer, generally 250–350 mm thick, as shown in Fig. 1. It has the following functions [1–3]:

- Resistance to the sleepers against vertical, longitudinal and lateral displacements, thus providing a stable support for trains to ride.
- Transferring the train forces to the subgrade thus reduce the compressive stresses on it. This helps prevent the stresses in the subgrade from exceeding the bearing capacity.
- Maintaining track geometry in the vertical and lateral directions.
- Adjustment of the elasticity and stiffness of the whole track structure (fines and fouled ballast).
- Insulation properties to avoid interference with track power supply.
- Drainage permeability and absorption of noise and vibration.
- Suppression of vegetation growth on the track.

To fulfil the ballast layer function, the ballast material itself should meet certain characteristics, including: particle size, particle shape, particle gradation, surface roughness, particle density, bulk density, strength, hardness, impact toughness, wear resistance and weathering resistance [4–6].

Ballast materials are generally high quality igneous or metamorphic rock, which were blasted during mining and sieved to obtain desirable ballast particles. Although ballast particles are traditionally specified as uniformly graded, irregularly shaped, hard and with a rough surface, the ballast standards vary from country to country due to the quality of the rock, its suitability, environmental regulations, economics and the source of the parent rock. For example, prior to the 1870 s, the material selection for ballast did not focus on the ballast material or its physical properties, but often prioritised the price of raw materials and transport

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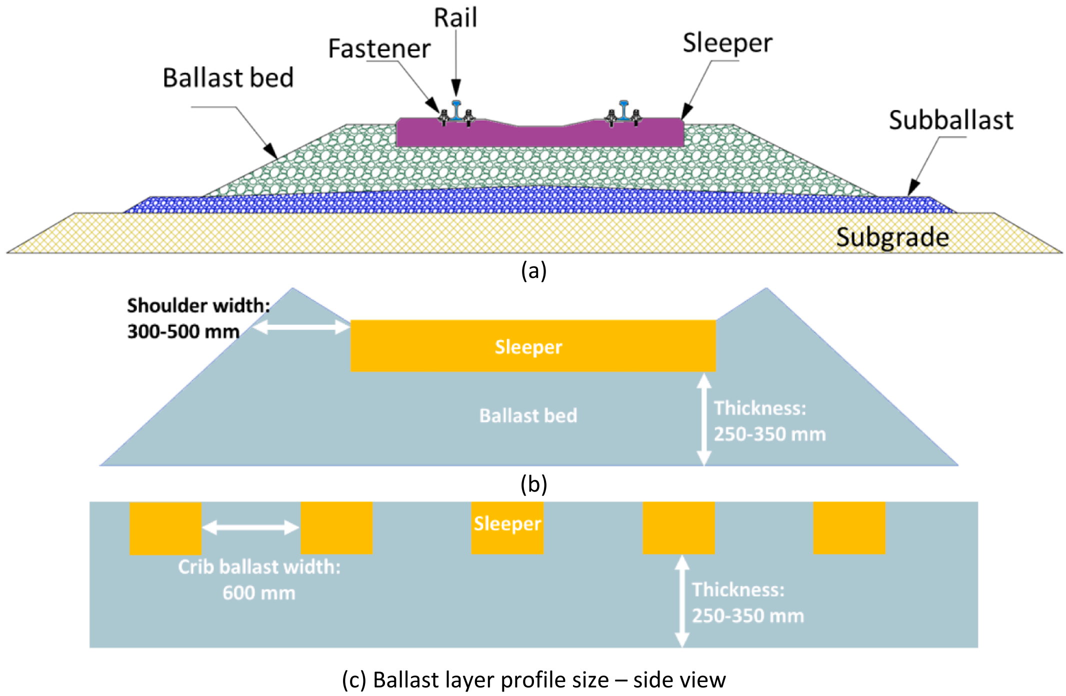


Fig. 1. Ballast track and ballast layer profile size: (a) Common railway ballasted track; (b) Ballast layer profile size – front view (c) Ballast layer profile size – side view.

costs [2].

To date there are no international uniform standards (applicable for most conditions) regarding the physical and mechanical properties of ballast, such as wear resistance and mineral composition. For example, when selecting ballast in different countries, different types of parent rock materials such as basalt, granite, limestone, dolomite, rhyolite, gneiss and quartzite are considered. These ballast materials are selected differently depending upon country, often depending on load types of trains (passenger, freight), operating environment (temperature and moisture) and foundation conditions [4].

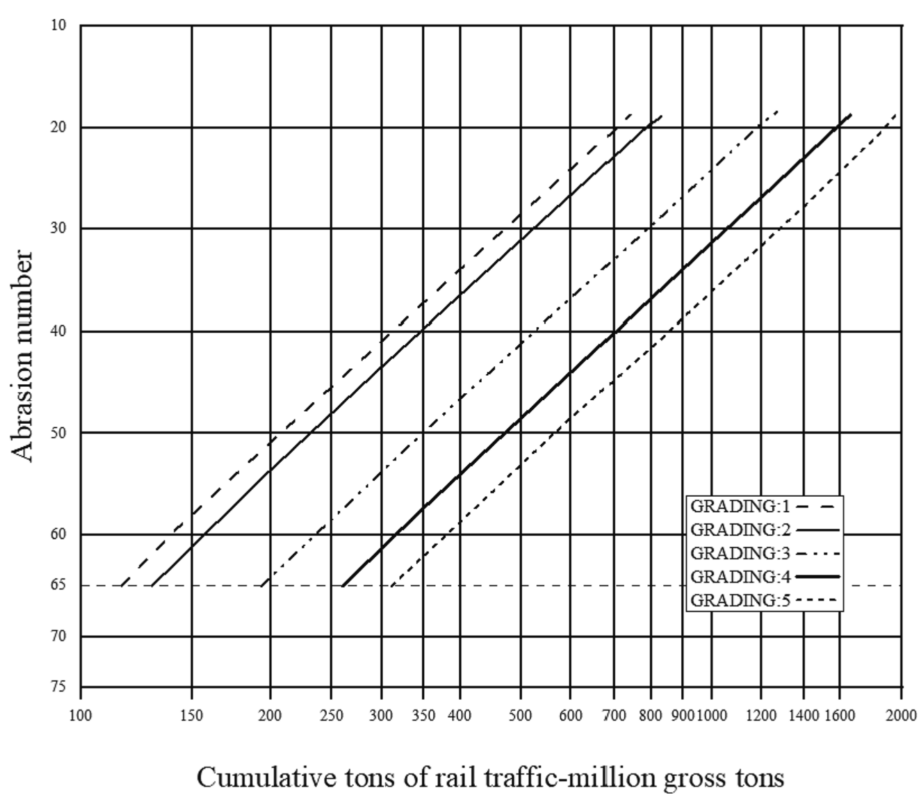


Fig. 2. Cumulative tons of traffic versus abrasion number (figure).
reproduced from [10]

Table 1
Overview of historical ballast materials (modified after [15]).

Ballast materials	Advantages	Disadvantages	Applicability
Sand	Medium drainage, low price, good vibration and noise reduction, suitable for steel sleepers	Accelerated rail wear, poor wind resistance, poor compaction retention and inability to use on demanding railways, rapid degradation when wet	Suitable for railways with steel sleepers, not for high-speed railways
Moorum rock	Inexpensive, non-hydrophilic material, aesthetically pleasing	Soft texture, easily becoming fines, difficult to maintain and repair, rapid degradation when wet	Sub-ballast, initial track fill for new lines
Coal ash, cinder	Easy to obtain, inexpensive, good drainage	Corrosion of rail sleepers and rails, soft surface texture, easily becoming fines, difficult to maintain and repair, rapid degradation when wet	Emergency repairs after slopes, floods, etc., not applicable to high-speed railways
Crushed rocks	Hard, durable, good drainage, high stability - elasticity - toughness, more economical in the long term	Higher initial cost, poor mountain resources in some countries, more damage to wooden sleepers	Combined with large machinery, applicable for medium and high-speed railways and heavy haul

This paper summarises the ballast technical standards used in various countries as well as the evaluation methods and corresponding laboratory tests for ballast materials in earlier studies. The ballast material selection methods for different conditions (geology, environment, etc.) are highlighted, providing important references for ballast selection in complex situations such as multi-geographic areas. The paper structure is as follows:

1. Ballast materials. This section includes a general introduction of ballast materials, ballast material qualification tests and methods for ballast material quality classification.
2. Ballast parent rock. This section discusses parent rock types, the mechanical performance of each parent rock, limestone application as ballast, specifications/requirement for parent rock and parent rock quarrying and weathering.
3. Ballast morphology. This section discusses ballast size, ballast shape and multi-layer ballast.
4. Ballast petrography. This section introduces the mineral compositions of ballast, and its effects on ballast performance.
5. New ballast and environmental impacts. This section discusses promising new ballast materials and their environmental impacts.

2. Ballast materials

2.1. Introduction

Material properties influence the ballast layer lifespan, and further the ballasted track lifespan. In the early days of railway construction and operation, the focus was usually on particle size distribution (PSD) rather than on the ballast material. In the UK, for example, it was not until the late 1980 s that emphasis was placed on the mineralogy of the rock material. Because of the rock resource availability, most of the rock type used on the British rail network was historically limestone in the early years [7].

Besides the crushed rocks, ashes, sand, slag, broken bricks, clay, and other materials were also used as ballast sources. Ash was once considered a good ballast material due to providing the rapid drainage and the good contact between ash and the sleeper bottom. Even as late as 1922, nearly 90% mileage of the former North Eastern railway was ballasted with ash in USA. The book [8] states ash could be used as an alternative to ballast, but the presence of sulphides in the ash was a strong chemical hazard to the sleepers and also other track components. Therefore, ash was removed from the list of acceptable materials for railway ballast materials [9].

Table 2
Ballast material selection and testing methods (modified after [2]).

Property classification	Ballast properties	Testing methods	Evaluation terms
Mechanical properties	Hardness, strength	Los Angeles Abrasion test	Abrasion, wear and crushing
	Hardness	Deval abrasion test: dry and wet grinding	Surface wear
	Hardness	MDA test	Surface wear
	Strength	Single particle crush test	Crushing resistance
	Hardness	Scratch hardness	Surface wear-resistance into fines
	Strength	Point load strength test	Fragmentation into small pieces
	Impact toughness	Drop weight test	Resistance to impact loading and crushing
	Hardness	Dorry abrasion test	Surface wear-resistance into fines
	Hardness	Mill abrasion test	Surface wear-resistance into fines
Physical properties	Grading	Gradation measurement	Drainage, compactness
	Grading	Small particle/dust measurement	Drainage properties
	Physical Stability	Particle density measurement	Displacement resistance, indirect strength
	Physical Stability	Bulk density measurement	Porosity, drainage, track stability (lateral, longitudinal, vertical)
	Shape Characteristics	Particle profile measurement	Breakage into multiple small pieces, drainage
Chemical properties	Chemical stability	Damp-dry resistance test	Durability, weathering resistance
	Chemical stability	Freeze-thaw test	Durability, weathering resistance
	Chemical stability	Particle Porous Structure Test	Durability, weathering resistance
	Chemical stability	Particle water absorption	Saturation, weathering resistance
	Chemical stability	Sodium and magnesium sulphate solution test	Durability, weathering resistance
	Chemical stability	Clay clods and friable particles	Durability, initial abrasion level
Ballast layer properties	Ballast layer profile	Bed thickness, shoulder and slope measurements	Rail stability, elasticity, damping
	Layering	Geometric position testing	Rail stability, comfort

In [10], it is suggested that the service life of ballast layer at different classes (grading) can be estimated by the abrasion number (AN) of the ballast material, as shown in Fig. 2. How to calculate AN is explained in Table 6. Fig. 2 also shows that there is a significant difference in the service life of ballast materials. It is easy to see that when a more wear resistant material is used, such as granite rather than limestone, the AN value decreases and the ballast life increases significantly. This finding is in line with that in the study of [7]. This also suggests that the choice of ballast should tend towards materials that have high resistance to wear and impact.

Ballast layer capacity has become increasingly important, because of increasing train speeds and heavier haul. Since ballast layer became an

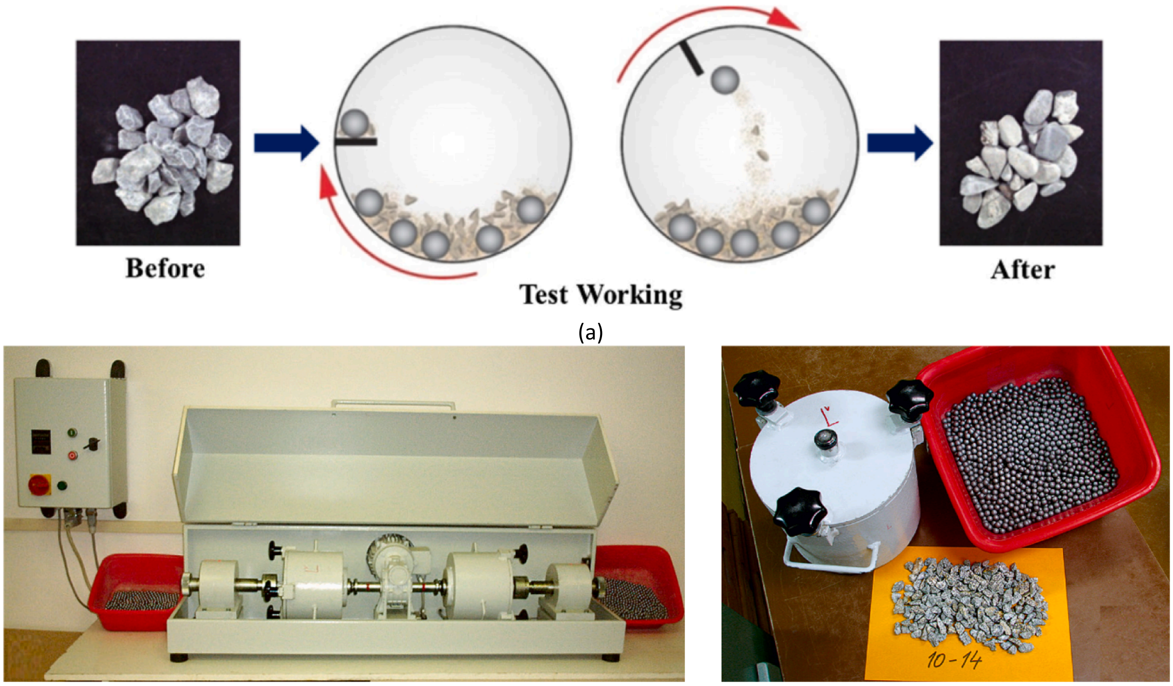


Fig. 3. Traditional and commonly-used test rigs for testing ballast properties: (a) Los Angeles Abrasion test rig; (b) Micro-Deval abrasion test rig; (c) sample, steel balls and test rig drum (figure).
reproduced from [19,20]

important component of ballasted track, it has been enhanced on the stability and suitability for complex environments. As shown in Table 1, initially ballast material could consist of simple gravel or ore, which has the disadvantages of being easily broken and having poor load-bearing capacity. As the increase of train speeds and axle load, there are more demanding requirements for ballast particles and ballast layer, such as narrower PSD, higher particle strengths and higher particle densities. Note that the use of rushed rocks as ballast material increases the difficulty of manual maintenance. The railway maintenance mechanisation has already been well advanced, but intelligence needs to be further strengthened to improve preventive maintenance to precise spot maintenance [11–14].

2.2. Ballast material qualification tests for crushed rocks

In earlier studies and standards [1,4,5,16], the authors have summarised the relationship between the mechanical, physical, environmental and geometric properties of the ballast layer and ballast materials. In addition, they have summarised the test methods to determine each property of the ballast materials, as shown in Table 2. Note that two traditional and commonly-used tests are Los Angeles Abrasion (LAA) test and micro-Deval abrasion (MDA) test, and their machine/rigs for testing these ballast properties are shown in Fig. 3. Deval abrasion test was replaced by MDA test, because the MDA test can better test ballast properties [17]. The mill abrasion (MA) test is a relatively new test being proposed for use in North America [18].

Table 3
Correlation between micro-Deval abrasion rate and factors [16].

Factor	Correlation	Factor	Correlation
Average mineral grain size	No clear correlation	Micro-cracks	No correlation (the water absorption value is<1 %)
Water absorption	No clear correlation	Angularity	MDA rate reduces as it increases
Specific density	Slight correlation	Surface roughness	MDA rate reduces as it increases
Soft minerals (mica, chlorite and carbonate)	MDA rate increases as it increases	Quartz	Poor correlation

Fundamentally, all kinds of abrasion tests were chosen for assessing ballast quality because more wear-resistant rocks have higher density, uniaxial compressive strength, tensile strength, Shore hardness, point load strength and lower porosity. In the following paragraphs, these abrasion tests are briefly introduced. The LAA test and MDA test are the most popular ones, for which they are compared and analysed.

2.2.1. Los angele abrasion test

[21] used laboratory tests to show that those rocks with low LAA rate have high density, compressive strength, tensile strength, hardness, point load index and P-wave velocity values. The comparison of LAA test requirement in different standards is shown in Table A1.

In addition to the mechanical properties of the ballast particles, factors such as the shape and size of the ballast particles also have an influence on the LAA rate of the ballast particles. For example, in [22], LAA test was performed on limestone ballast particles and compared the 2D images of these ballast particles. The results showed that the ballast particles were more likely to crush in the early stages of the LAA process due to the sharp corners and edges of the larger particles, while the smaller ballast particles tended to be more spherical in shape and therefore produced less powder by abrasion. Afterwards, as the ballast particles become smoother and more rounded, and thus more resistant to wear and fracture. This is consistent with the findings in [23–25]. This means that higher angularity of aggregate exacerbated the degradation level due to increment of breakage potential [26]. Besides, in [27] it was confirmed that freshly crushed ballast particles have higher angularity compared to natural cobbles and recycled ballast, for which the fresh ballast can provide higher shear strengths. This conclusion is consistent with that in [28,29]. It can therefore be inferred that ballast particles with larger particle sizes have greater LAA rate and poorer wear resistance, but higher shear strength.

Table 4
Comparison of MDA test and LAA test [30].

Test Procedures			LA Abrasion (Grading C)[a]	Micro Deval (Grading Z)[b,c]
Standard test fraction			2.36–9.55 mm	2.36–9.55 mm
Sieve size (mm)				
Grading	Passing	Retained on		
	9.5	6.7	2500 ± 10 g	750 g
	6.7	4.75	2500 ± 10 g	750 g
Total			5000 ± 10 g	1500 g
Number of balls			8	–[d]
Charge of steel balls (g)			3300 ± 20	5000 ± 5
Water			–	2L
Speed of the drum (rpm)			30–33	5000 ± 10 g
Revolutions (time)			500	–
Number of parallels			1	2
Retain on sieve for calculating the LA Abrasion (%) and Micro Deval (%)			1.7 mm	1.18 mm
Apparatus	Internal diameter of the drum		710 mm	200 mm
	Internal length of the drum		510 mm	178 mm
	Diameter of each ball		48 mm	9.5 ± 0.5 mm
	Weight of each ball		390–445 g	–[d]

Note:
a NZS 4407:1991 Test 3.12 - The abrasion resistance of aggregate by use of the LA machine.
b ASTM D6928-10 - Standard test method for resistance of coarse aggregate to degradation by abrasion in the Micro - Deval apparatus.
c Materials requirement for Micro Deval tests.
d There is no specific information regarding to the weight and the number of the steel balls used in Micro Deval tests in ASTM D6928-10. However, the total steel charges to be put in to the drum have to be 5000 ± 10 g, as specified in the standard.

2.2.2. Micro-Deval abrasion test

It was first used for the testing of road base aggregates, where the particle sizes were generally in the range of 10–14 mm. Afterwards, it was later extended to the testing of railway ballast, where the particle sizes were generally in the range of 31.5–50 mm.

The MDA test has many factors influencing the test results, which are given in Table 3. From the table, the shape has the biggest effect on the MDA rate, and the mineral composition is second (explained more in Section 5). The specific density and micro-cracks have no clear correlation.

2.2.3. Comparison of LAA test and MDA test

The LAA test is performed only on dry ballast particles, while the MDA test can be performed on dry or soaked ballast particles. Table 4 shows the comparison of MDA test and LAA test. In [30], it was shown that ballast particles are less susceptible to degradation when soaked in water. MDA test tends to polish (smooth) ballast particles, while LAA test tends to crush them [31]. Two details about the reasons making the two tests different are given as follows.Table 5.

- The steel balls for the two tests are very different (LAA test: 48 mm diameter; MDA test: 9.5 mm diameter). Additionally, the drop distances of the steel balls are also of great difference, because the drum diameters of LAA test and MDA test are different. LAA test drum diameter is larger than MDA test drum diameter, and LAA test applies heavier steel balls, for which LAA test applies large impact loading. Thus, ballast particles are crushed more in LAA tests.
- The LAA test normally applies 5 kg of ballast particles, while MDA test only applies 1.5 kg. Thus the LAA test applies>3.3 times heavier ballast particles than MDA test, which increases possible effective fragmentation in the LAA test. In addition, the sieve size for LAA test is 1.7 mm, which is larger than that for MDA test (1.18 mm). Thus, more crushed particles can pass through the sieve, for which higher percentage loss is caused by the LAA test.

2.2.4. Deval abrasion test

This test was standardised from 1951 and was used for the assessment of railway ballast in UK (BS 812:1951) [18]. The Deval abrasion test was used in the Austrian ballast standard until the 1960 s. This test was finally replaced by the MDA test in 2004 [17]. Two kinds of derived tests from Deval abrasion test are wet abrasion test and dry abrasion test, which are carried out in a dry state or by adding an equal amount of clean water. Almost no particle crush happens during the tests, because the impact loading is small. The reason of small impact loading is that the test rig drum is small. The main factor influencing the Deval abrasion test results is particle size. In addition, the test rig drum can have angles with the horizontal plate, which also has effects on the abrasion rate. Because there are limited studies about Deval abrasion test in the earlier studies, and it has been replaced by the MDA test as stated in Section 2.2.2.

Regarding adding the water, it was proved in many studies that water reduces the shear strength of ballast particles [28,32]. Normally, the ballast layer drainage is enough to dry out the water. However, fouling inevitable accumulates in ballast layer, which jams the voids in ballast layer causing drainage problem. The stored water mixed with fouling causes the phenomenon of mud-pumping.

2.2.5. Mill abrasion test

MA test has a similar test procedure to the MDA test. Before the MDA test was proposed for railway ballast, researchers began to question the field reliability of the LAA test. This was because the LAA test was idealised by drying the ballast specimens, whereas in practice ballast is subjected to a complex and variable field conditions [16]. The MA test assesses different ballast properties from the LAA test. The MA test assesses the resistance of the particles against crushing and hardness of the particles, while the LAA test measures the strength or toughness of the particles [33,34]. The two tests are therefore considered to be complementary. Both Canada and France used a combination of these two tests to control the quality of ballast materials, which is called the abrasion number (AN). The MA specifications are given in Table 3.

Different tests and testing standards have been used in different countries for different ballast properties. The ballast standards used by Australian, US and EU are summarised, as shown in Table 6. From the table, it can be seen that ballast density is not specified, but only the

Table 5
Mill abrasion test specifications.

Region	Measurement content	Condition	Specimen mass	Water mass	Drum length	Drum volume	Revolution number
North America	Abrasion/wear resistance	Mixed with water	1500 g 19–25 mm and 1500 g 25–38 mm	3000 g	229 mm	3.8–5 L	10,000

Table 6
Summary of ballast standards (modified after [2]).

Property	Requirements	Australia	EU (EN13450)	USA (AREMA)
Physical properties	Particle size distribution (gradation)	AS 1141.11.1	EN933-1	ASTM-C136
	Dust ratio (No. 200 aperture sieve)	≤1%	0.5–1.5% (0.063 mm)	≤1%
	Content of clay lumps and friable particles	–	–	≤0.5%
	Particle density (kg/m^3)	≥2500 (dry)	EN 1097–2	≥2600
	Bulk density (kg/m^3)	≥1400 (AS1141.4) ≥1200 (NSW TN 061: 2015)	CEN 17892–2	≥1120
	Elongated particles	Length to slenderness ratio 2:1<30%	EN 933–3	Length to slenderness ratio 3:1<5%
	Flaky particles	≤30%	EN 933–3	≤5%
	Fresh fractured surface	Over 75% with two fresh fracture surfaces	–	–
	Drainage	–	CEN 17892–11	–
Durability and weathering resistance	Water absorption	–	EN 1097–6	≤2%
	Freeze-thaw cycle	–	EN 1367–1	–
	Sulphate soundness	–	EN 1367–2	≤5%
Mechanical properties	MDA test	–	≤5-15%	–
	Abrasion Tests	–	–	AN between 25% and 65%*
	Wet wear test	<6%, 8%, 12% for different railway classifications	–	–
	Los Angeles Abrasion rate	<25%, 30%, 40% for different railway classifications	12%-24%	≤30%
	Particle breakage ratio	<25%, 30%, 40% for different railway classifications	–	–
	Impact value	–	14%–22%	–
	Strength test	Wet: 175, 150, 110 kN for different railway classifications	–	Point load strength test: dry > 1200 kg. Moist > 800 kg
Ballast layer profile	Thickness	325, 275, 225 mm for different railway classifications	–	>12″ mainline railway
	Ballast shoulder width	400–700 mm seamless lines, 300–700 others	–	>12″ mainline railway
	Slope gradient	1:1.5	–	1:2
	Crib ballast height	To top of rail sleeper	–	–

Note: * AN = LAA rate + 5 × MA rate.

Table 7
Comparison of ballast evaluation limits in different standards [35].

Country/test	LAA test	MDA test	Aggregate crushing	Sulphate soundness
Australia (AS 1141)	25	–	25	–
Canada (CN)	20–30	–	–	7–10
UK (BS EN 13450)	20	7	22	–
USA (AREMA)	25–40	–	–	5
Germany (BS EN 13450)	8.7–23	–	–	–
India (IRS-GE-1)	30–35	–	–	–
Iran (IR301)	30	10–14	–	5

method of measurement of density is given in EU. However, minimum requirements for ballast particle density and bulk density are given in Australia and the USA. Nevertheless, until now it still lacks of a standardised method for measuring ballast density and bulk density in the field.

Table 9
Deutsche Bahn AG Requirements for Ballast [37].

Ballast Material	Los Angeles Test	Aggregate Impact value	Impact Resistance	Deval Test
Basalt	8.7–9.5	10	10.2–11.7	10.3–13.8
Porphyr	10.3	10	11.9	11.1
Sandstone	12.5	11	14	9.8
Limestone	13.7	15–23	16.3–21.3	5.9

2.3. *Ballast material quality classification*

Table 6 also shows that the Australian ballast requirements are more comprehensive and detailed, while the EU standard gives less specific values and the US standard is an old one (has been used since created without updates). Compared with these standards, the Chinese standard is more cautious in the selection of ballast material, especially ballast for high-speed railway, and generally aligns with the maximums shown in other standards. It can also be seen that the workload of specifying the same standard for different EU countries is greater, so only the standard test methods are given in the EU standard. The rest of the world mostly

Table 8
Difference of standard requirement before and after 2010 in Hungary [36].

Mechanical properties	LARB(%)				MDERB(%)			
	Between 2008 and 2009		Since2010		Between 2008 and 2009		Since2010	
Vlim(km/h)	Required value	Max. tolerance	Required value	Max. tolerance	Required value	Max. tolerance	Required value	Max. tolerance
V > 160	16	+2 (neg. is not limited)	16	–	11	+2 (neg. is not limited)	11	–
160 ≥ V ≥ 120	16	+4 (neg. is not limited)	16	–	11	+4 (neg. is not limited)	11	–
120 ≥ V ≥ 80	16	+4 (neg. is not limited)	16	–	11	+4 (neg. is not limited)	15	–
80 ≥ V ≥ 40	24	+4 (neg. is not limited)	20	–	15	+4 (neg. is not limited)	15	–
V < 40	24	+4 (neg. is not limited)	24	–	15	+4 (neg. is not limited)	15	–

Table 10
Ballast quality classification in different standards [35].

Class	Ballast condition	LAA test	MDA test	Aggregate crush	Sulphate soundness
A, 1 or I	Clean	5–10	0–5	0–10	0–2
B, 2 or II	Moderately clean	10–20	5–10	10–20	2–5
C, 3 or III	Semi-fouled	20–30	10–14	20–25	5–7
D, 4 or IV	Fully-fouled	30–50	14–20	25–40	7–10

refers to the British standard, while individual countries include some specific required items according to their own circumstances. The commonly-used acceptance limits for ballast in the standards of different countries are given in Table 7.

Note that the requirements in standard keep being changed with the development of railway, such as train speed. For example, in the Hungarian standard, the required values for the LAA rates (tracks under all train speeds) were reduced in 2010 [36], as shown in Table 8.

Further Germany also requires different test values for different ballast materials, as shown in Table 9. The possible reason is different ballast materials have different LAA rate but similar performance. However, this has not been fully proved in any earlier studies. More details about other factors influencing the LAA rate are explained in Section 3 and Section 5.

Based on the ballast properties and corresponding tests in Table 2-Table 8, the ballast quality classifications in each standard are summarised in Table 10. From the table, it can be seen that the quality is classified based on the degradation and weathering resistance. However, the field conditions are much more complex, including water, temperature, etc., for which the classification could include more tests concerning the ballast parent rock type (e.g. mineral composition), ballast shape and size, etc. These tests for assessing ballast properties are discussed in the following sections.

In some of standards (e.g. US, China) each ballast particle must possess at least three fresh fracture faces. The fresh fracture face means the face is new and with enough roughness. In addition in [10], it also requires the size of the fresh fracture faces, as shown in Fig. 4. Specifically, the largest dimension of the fresh fracture face must be at least one-third of the maximum particle dimension, and the smallest dimension of the fresh fracture face must be at least one-quarter of the maximum particle dimension, as shown in. The angle formed by the fractured face and adjacent faces must be $<135°$, then the fracture face is considered a separate fractured face. This requirement, along with the requirement of having three fresh fracture faces, eliminate the possibility of the flaky, shard-like particles (that are common in hard, fine-grained rock) as suitable ballast particles. However, no evaluation methods have been found in any literature. In addition, manual observation of fracture faces is time-consuming and prone to interpretation error.

3. Ballast parent rock

3.1. Parent rock types

Ballast is generally made of artificially crushed natural rock. This parent rock is classified into three main categories (rock class): igneous, sedimentary and metamorphic; depending on the conditions of formation [38], as shown in Table 11.

Igneous rocks are formed from cooled magma (hot molten liquids of

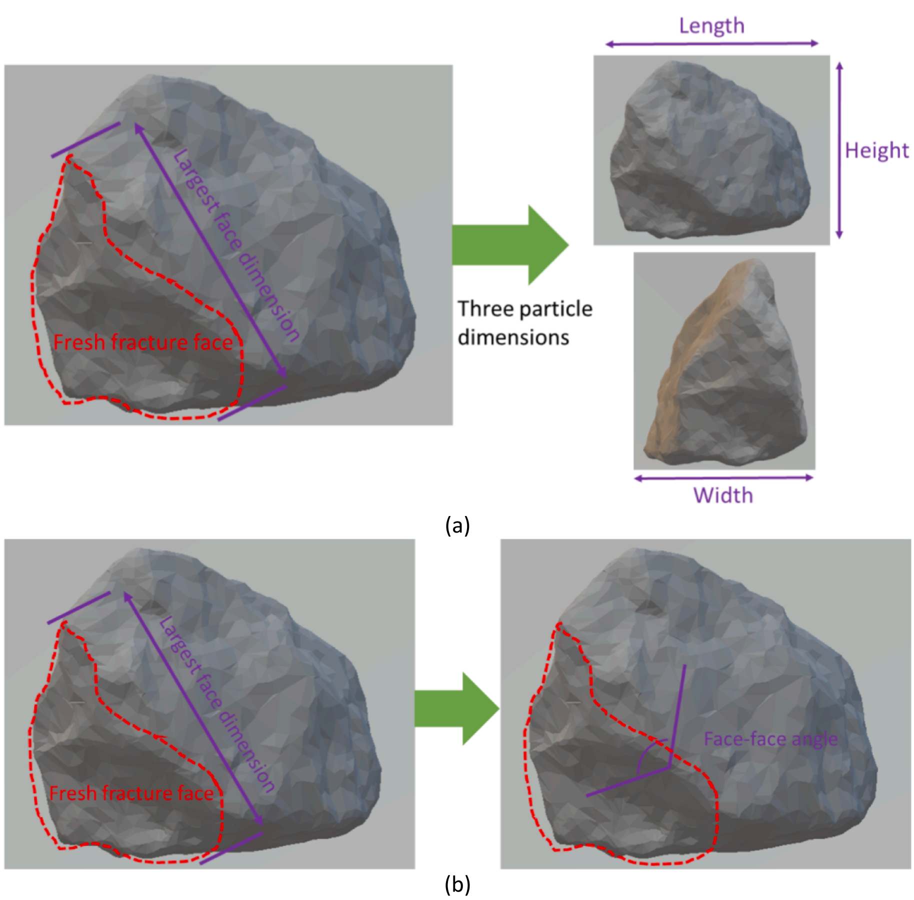


Fig. 4. Explanation for fresh fracture face size and fractured face angle: (a) Fresh fracture face size; (b) Fresh facture face angle.

Table 11
Classification of common rocks in nature [38].

Parent rock class	Rock genesis	Rock type
Igneous rocks	Magmatic rocks, formed by the rising and cooling of molten magma within the earth's crust. Depending on the conditions of cooling, they are divided into three categories: deep-formed rocks, ejecta and volcanic rocks.	Commonly found in engineering are granite (deep-formed rocks), basalt, andesite and gabbro (ejecta). The volcanic rocks are mainly basalt, andesite, argillite, rhyolite and rhyolite, while the deep-formed rocks are granite, granodiorite, anorthite, gabbro, amphibole, gabbro, porphyry, siderite, gabbro and porphyry.
Sedimentary rocks	Rocks formed by the weathering of the original parent rock and then transported, deposited and recreated, also known as hydromorphic rocks. Depending on the mode of deposition, sedimentary rocks can be classified as mechanically deposited, chemically deposited and biologically deposited rocks	Commonly found in engineering are limestone, dolomitic limestone, dolomite, travertine and sandstone.
Metamorphic rocks	Primary igneous or sedimentary rocks formed by geological metamorphism	Common in engineering are gneisses and quartzites. Marble, hornblende, gneiss, granite gneiss, schist, hornblende schist, mica schist, gabbro, serpentine, metamorphic rocks and rhodochrosite.

silicates and other compounds). The rate at which the magma cools determines the structure of the igneous rock formed. Ejected magma solidifies rapidly, forming glassy rocks or very fine rocks. Intrusive igneous rock forms as magma cools in the Earth's interior. As a result, it cools slowly and forms coarser-grained rocks. In general, the closer the intrusion is to the Earth's surface, or the smaller the size of the intrusion, the faster it cools and the finer the grain size of the minerals. In general, fine-grained igneous rocks are better in terms of strength than sedimentary or metamorphic rocks. Medium to coarse-grained igneous rocks and hard sedimentary rocks can also be used for engineering (e.g., railway ballast). Rock types such as shale and slate, which produce flakes or elongated particles, are less desirable because the particles do not interlock well with each other meaning the ballast deteriorates quickly when subject to vibration [39].

3.2. Parent rock mechanical performance

The different rock types influence the track serviceability. For example, in [40], the effect of rock strength on ballast degradation and settlement was studied. The rock strength was evaluated by the uniaxial compression test on intact rock core specimens. High compression values of the intact rock core reduced the settlement rate of ballast. This means that high strength parent rock leads to reduced ballast layer deformation. In addition, high compression values also increases the ballast layer stiffness, and reduce the ballast layer damping and elasticity. Perhaps most importantly, the ballast degradation reduced, which is presented by the ballast breakage index (BBI, see [41]).

In [42], the performance of aged basalt ballast that had been significantly worn and crushed (after long-term service) was compared against newly crushed granite ballast. Results showed that 63% of the aged basalt ballast had higher shear strengths in triaxial tests, but had low angularity. This means although the angularity loss has a degrading effect on the performance of the basalt ballast layer, this is compensated

Table 12
LAA rates of different parent rock types [39,43–46].

Parent rock type	Los Angeles Abrasion rate (%)
Basalt	10–17
Dolomite	18–30
Gneiss	33–57/16–21
Limestone	19–30/21–41
Quarzite	20–35
Granite	27–49/34–39
Igneous	15.4–18.9
Andersite	13.9–24.6/15.4–18.9
natural gravel	27–34
Sedimentary	20.5–41.2
Metamorphic	22.6–36.3
Marble	22.6–36.3
Natural pebbles crushed in a crusher	23–25

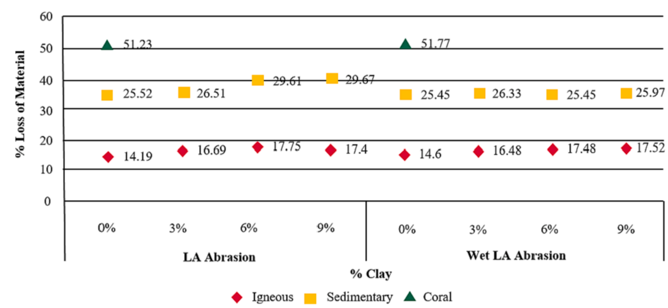


Fig. 5. Dry and wet LAA rate of three parent rock types (figure modified after [30]).

Table 13
MDA rate of two rock types from igneous origin [20].

Rock type	Rock class	MD min value (%)	MD max value (%)	No. of samples	Average	Reference
Basalt	Igneous	7	13	9	9	Apaydin and Murat (2019)
Granitoids	Igneous	2	19	17	8	Johansson et al. (2016)
Gabbroids		7	11	9	9	

by the basalt material, so that the mechanical properties of the aged basalt ballast are not lower than those of the newly crushed granite ballast.

This also indicates that the choice of a suitable ballast material can slow the deterioration of the ballast layer performance. However, during the triaxial tests, the strength curve of the basalt ballast changes more slowly in the early stages, most likely due to the lack of interlocking between the basalt ballast particles. This makes it easier for the particles to further rearrange themselves by relative slip. The triaxial tests also showed significant differences in the volumetric strains of the two types of ballast. The initial shrinkage of basalt ballast is much greater than that of granite ballast. This means at the beginning of service, the deteriorated basalt ballast layer is more prone to deformation and settles more.

Yilmaz [43] analysed the physical and mechanical properties of 32 rocks by regressing LAA rate on the physical and mechanical properties of the rocks in LAA tests (Table A2). Among the tested rocks, igneous type rock samples showed more resistance to abrasion than sedimentary and metamorphic type rock samples. Specifically, in [44] the LAA rates of different parent rock types are given as shown in Table 12. This study also shows that igneous is a suitable choice for ballast.

In [30], three types of parent rocks were compared: igneous,

Table 14
Parent rock types and properties based on different testing standards.

Sample ID	Lithology	Source district	LA fragmentation resistance (%) (EN 1097–1)	Thermal weathering resistance (%) (EN 1367–2)	Polishing resistance (PSV) (EN 1097–8)	Dry Unit weight (g/cm3) (EN 1097–6)	Water absorption(%) (EN 1097–6)
LS-1	Limestone	Antakya-Kirikhan	24.4	2.4	41.2	2.7	0.4
LS-2	Limestone	Mersin-Tarsus	16.2	3.0	43.2	2.7	0.2
LS-3	Limestone	Adana-Ceyhan	24.4	8.1	41.6	2.7	0.3
BS-1	Basalt	Niğde-Bor	12.0	6.9	61.0	2.6	2.0
BS-2	Basalt	Kayseri	25.9	9.4	52.4	2.7	1.4
BLD	Boulder	Kaharamanmaras-Aksu	17.6	6.2	57.9	2.7	0.9
EAF-1	EAF Slag	Antakya-ìskenderun	22.9	2.3	76.1	3.4	1.8
EAF-2	EAF Slag	Osmaniy	25.3	8.3	59.0	3.4	2.5
EAF-3	EAF Slag	Antakya-ìskenderun	29.7	3.7	54.1	3.3	2.9
FER	Ferrochrome slag	Elaziğ	16.5	6.1	61.7	2.9	1.1

Table 15
MDA rates for each parent rock type and statistical analysis.

Standards	MDC results	Sample ID LS-1	LS-2	LS-3	BS-1	BS-2	BLD	EAF-1	EAF-2	EAF-3	FER
ASTM D 6928	MDC_1 (%)	11.1	17.2	10.8	7.0	9.7	7.9	7.3	7.2	8.5	8.5
A	MDC_2 (%)	10.2	17.5	10.7	6.8	9.8	8.4	7.2	7.5	9.9	8.1
(9.5–12.5–19.0)	$MDC_{Avg.}$ (%)	10.6	17.3	10.7	6.9	9.7	8.2	7.2	7.3	9.2	8.3
	CoV	1.0	1.7	1.0	0.7	0.9	0.8	0.7	0.7	0.9	0.8
	St	0.4	0.2	0.0	0.1	0.1	0.2	0.0	0.2	0.7	0.2
ASTM D 6928	MDC_1 (%)	9.2	16.1	9.7	6.1	6.8	8.0	8.3	8.2	13.1	8.1
B	MDC_2 (%)	8.9	16.5	9.7	6.2	6.8	8.3	7.7	7.8	11.4	8.5
(4.75–9.5–12.5)	$MDC_{Avg.}$ (%)	9.0	16.3	9.7	6.2	6.8	8.1	8.0	8.0	12.2	8.3
	CoV	0.9	1.6	0.9	0.6	0.7	0.8	0.8	0.8	1.2	0.8
	St	0.1	0.2	0.0	0.0	0.0	0.2	0.3	0.2	0.9	0.2
ASTM D 6928	MDC_1 (%)	8.8	15.4	7.3	5.7	7.0	7.5	6.6	5.5	7.9	5.3
C	MDC_2 (%)	8.8	15.6	7.1	5.2	6.7	7.7	6.2	5.4	7.2	5.4
(4.75–6.3–9.5)	$MDC_{Avg.}$ (%)	8.8	15.5	7.2	5.5	6.8	7.6	6.4	5.5	7.5	5.3
	CoV	0.8	1.5	0.7	0.5	0.7	0.7	0.6	0.5	0.7	0.5
	St	0.0	0.1	0.1	0.3	0.1	0.1	0.2	0.0	0.4	0.1
EN 1097–1	MDC_1 (%)	10.3	20.6	11.8	9.4	10.5	12.1	9.6	9.2	12.4	7.6
14.0–12.5–10.0)	r_1	2.1	3.3	2.3	2.0	2.2	2.3	2.1	2.0	2.4	1.8
	MDC_2 (%)	10.8	22.0	11.6	9.3	10.3	11.1	9.5	8.4	12.2	7.6
	r_2	2.2	3.4	2.3	2.0	2.1	2.2	2.0	1.9	2.3	1.8
	$MDC_{Avg.}$ (%)	10.6	21.3	11.7	9.4	10.4	11.6	9.5	8.8	12.3	7.6
	St	0.2	0.7	0.1	0.1	0.1	0.5	0.0	0.4	0.1	0.0

Cov: Coefficient of variation, St: Standard deviation, r: Repeatability

sedimentary and coral as shown in Fig. 5. The coral has very high LAA rate, which is not suitable as railway ballast on a high tonnage railway (such as high speed railway). In addition, it can be seen that the dry or wet test conditions have little effect on LAA.

Some earlier studies applied MDA to assess parent rock performance. For example, in [20], three types of parent igneous rocks were compared, basalt, gabbroid and granitoids, as shown in Table 13. These rock types show same average MDA rate, but the granitoids have a wider MDA rate range (2–19%). This means the rock type has same MDA rate, but possibly different performance.

In [47] rock mechanical parameters and an indicator for predicting its long-term performance were studied for several types of parent rock, as shown in Table A3 and Table A4. From Table A3, it can be seen that even for the same parent rock type but from different quarries, the MDA rates are quite different. Table A4 shows that parent rock type has decisive role in predicting its long-term performance, however, the mineral composition for different samples can be very different. Thus, it is necessary to analyse parent rock on the scale of minerals (Section 5).

In [31] by considering different standards, three types of parent rocks and two types of steel slag were assessed though MDA tests. The results are given in Table 14, and MDA rates for statistical analysis are given in Table 15. From the tables, it can be seen that the testing standards in different countries also affect the test results, which were not focused in many of the earlier studies. Therefore, there is an opportunity to develop a more detailed and universal standard.

Table 16
Rock characterisation.

Rock types	Range of CA indicators	Range of CB indicators	Qualification rate of special ballast, first class ballast
Granite	5%<CA < 20%	12%<CB < 26%	28.15%
Basalt	3.5%<CA < 9%	8%<CB < 22%	76.3%
Andesite	3%<CA < 9%	8%<CB < 18%	100%
Limestone	6%<CA < 18%	18%<CB < 28%	0

3.3. *Limestone application as ballast*

Limestone is susceptible to degradation due to rainfall, which makes it difficult to ensure the track stability. However, it can be used as ballast in some limited parts of the world where the climate is dry (e.g. desert areas), and in these situations it can provide high load-bearing capacity. Standards in China for rocks used as ballast are shown in Table 16. In the table, CA and CB are two indicators, which are standard aggregate crushing rate (CA) and ballast collect stuff crunch rate (CB) in field tests, respectively. The CA measures the particle sizes at 10–16 mm, while CB measures 16–63 mm particles with certain particle size distribution.

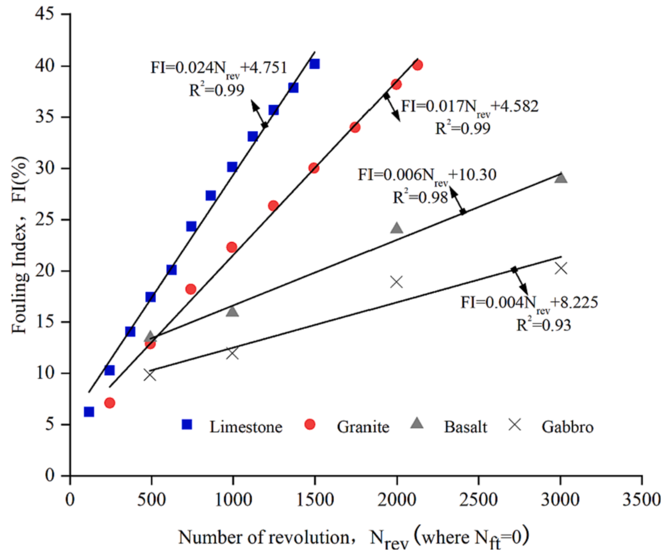


Fig. 6. Fouling index vs LAA rate of four kinds of ballast materials (figure). reproduced from [51]

Table 17
Standards for ballast material durability.

Specification	LAA rate (%)	MDA rate (%)	Los Angeles abrasion rate + MDA rate (%)	Requirement
Portugal IT. GEO.006 [54]	≤25	≤18	<40	All
UIC Code 719R, International Union of Railways [54]	≤20 or ≤ 25 (28 in some railway lines)	≤15 or ≤ 20 (22 for some areas of the roadbed)	<40 (train operating speed ≥ 160 km/h) <50 (train operating speed < 160 km/h)	One of them
French SNCF (2001) [54]	–	–	≤40 (train operating speed ≥ 160 km/h)	–
Spanish FOM (2006) [54]	≤28	≤22	–	All
China TB/T 2140–2008 [48]	≤18 (Special class ballast); ≤27 (first class ballast)	–	–	All
British standard BS EN 13,450 [55]	≤24	≤14	–	All

In the Chinese standard, the two indicators (CA and CB) determine whether the rock type can be used as ballast or not. The table shows that the crushing resistance of limestone does not meet the requirements of the current Chinese specification TB/T2140-2008 [48] for first-grade or special class ballast, and is not qualified to be the parent rock for railway ballast. The special class ballast is the highest quality ballast. On Chinese high-speed railway lines the special class ballast must be used. Basalt and andesite parent rocks typical meet the requirement. However, granite has a lower pass rate, but can also meet the CA and CB specifications.

Regarding limestone, a linear multiple linear regression analysis was carried out to predict LAA rate and fouling index (FI) considering areas with high traffic loads and high sensitivity to frost. Results showed that limestone had the worst performance [49]. Selig also carried out a wet abrasion value test on granite and limestone, which showed that the abrasion resistance of limestone was much lower than that of granite, indicating limestone is not a preferred material for ballast, either in terms of strength or abrasion resistance [5,50].

Table 18
Chinese ballast properties and test evaluation.

Properties	Evaluation Parameters	Special class ballast	Class One ballast	Requirement
Abrasion and impact resistance	Los Angeles abrasion rate (LAA; %)	≤18	18 < LAA < 27	–
	Aggregate Impact Toughness (IP)	≥110	95 < IP < 110	one of them
	Wear-resistance factor (K; dry grinding)	>18.3	18 < K ≤ 18.3	
Crush resistance	Standard Aggregate Crush Rate (CA; %)	<8	8 ≤ CA < 9	–
	Ballast Aggregate Crush Rate (CB; %)	<19	19 ≤ CB < 22	–
Water permeability	Permeability coefficient (P_m; 10^{-6} cm/s)	>4.5	>4.5	At least two of them
	Compressive strength of dust using test mould pieces (σ; MPa)	<0.4	<0.4	
	Stone powder liquid limit (LL; %)	>2050	>2050	
	Stone powder plastic liquid limit (PL; %)	>11	>11	
Atmospheric corrosion resistance	Loss by immersion in sodium sulphate solution (L; %)	<10	<10	–
Stability performance	Density (ρ; g/cm3)	>2.55	>2.55	–
	Unit weight (R; g/cm3)	>2.50	>2.50	–
Particle shape and cleanliness	Elongated index, flaky index (%)	≤20	≤20	–
	Particle surface cleanliness (%)	≤0.17	≤0.17	–
	Content of weathered particles and other miscellaneous stones (%)	≤2	≤5	–
	Mass percentage of content of powder with particle size below 0.1 mm (%)	≤1	≤1	–

As shown in Fig. 6, a linear multiple linear regression analysis was carried out to predict LAA rate and FI considering areas with high traffic loads and high sensitivity to frost, and the results showed that limestone performed the worst [51]. In the figure, results from the two studies, [22,53], were used for comparison.

For the use of limestone as railway ballast, however, there are many cases in many countries. For example, on the Portuguese Lisbon - Algarve line, due to the scarcity of local raw materials, limestone was used as ballast [54]. Specifically, the 30 mm thick granite ballast (initial design) was replaced by a combination of two parts: 15 mm thick granite and 15 mm thick limestone. While solving the material problem, it is also beneficial for the project cost. As shown in Table 17, the limestone in the case has a maximum LAA rate of 27% and a maximum micro-Deval abrasion (MDA) rate of 12%, which does not meet the IT. GEO.006 standard, but according to the relevant railway ballast standards of the UIC and some European countries, the limestone can meet the LAA rate and MDA rate requirements.

3.4. Other specifications on parent rock

Countries such as China have clear provisions for ballast raw

Table 19
US ballast physical parameters and test specifications [57].

Performance	Parameters	Granite	Dark coloured rock	Quartzite	Limestone	Dolomitic limestone
Abrasion and impact resistance	Los Angeles abrasion rate (%)	<35	<25	<30	<30	<30
Resistance to atmospheric corrosion	Loss by immersion in sodium sulphate solution (%)	<5	<5	<5	<5	<5
Water permeability	Water absorption (%)	<1	<1	<1	<2	<2
Stability	Gross volume relative density	>2.6	>2.6	>2.6	>2.6	>2.65
Ballast particle shape and cleanliness	Elongated index, flaky index (%)	<5	<5	<5	<5	<5
	Mass of clay and its impurity content (%)	<0.5	<0.5	<0.5	<0.5	<0.5
	Mass fines below 0.075 mm (%)	<1	<1	<1	<1	<1

materials, e.g. should be produced by crushing and screening rocks from mountains. In contrast, the Black Mesa and Lake Powell (BMLP) Railway in the USA does not use freshly fractured graded rocks in accordance with specifications, when performing the track rehabilitation due to a lack of local quarries. Their strategy was: aged ballast was allowed to make up 5% of the total ballast, and rounded coarse-grained river gravel obtained from the nearby Colorado River was crushed as the remaining 95% [56]. It was suggested that the crushed gravel should 99 % or more of particles, by mass, to have 2 or more acceptable fresh fracture faces, and 75 % or more of particles, by mass, to have 3 or more acceptable fresh fracture faces.

China's ballast requirements are mainly based on LAA rate, standard aggregate impact toughness IP, stone wear hardness factor and other indicators to control the ballast performance. The UIC and CEN member countries, including the UK, generally use indicators such as LAA and MDA rate [54]. Chinese ballast standards (both TB/T2140-2008 and TB/T2140-1990) uses material properties and parameter indicators for restrictions. The requirements for ballast properties in Chinese ballast standard [48] are shown in Table 18.

US AREMA also limits ballast materials according to parameters such as abrasion resistance and impact resistance, and on this basis specifies standard details, as shown in Table 19. It states cobbles and pebble-sized gravel can be used to produce crushed stone, and recommends the pebble-sized particles are firstly sieved by standardised sieves. The retained particles can be then used as ballast. Also, it recommends eliminating elongated and flaky particles [10].

Comparing US and Chinese standards the Los Angeles abrasion rate, the loss rate by immersion in sodium sulphate solution and density are common requirements. Regarding the Chinese standard, the special parameters are standard aggregate impact toughness, stone abrasion hardness factor, standard aggregate crushing rate (CA) and ballast collect stuff crunch rate (CB), permeability factor, compressive strength of stone dust test mould pieces, stone powder liquid limit and stone powder plastic limit. In contrast the special parameters in the American standard are water absorption, mass percentage of clay and its impurity content.

3.5. Parent rock quarrying stage and weathering

The parent rocks at different depths in the same mountain have different qualities due to weathering. Weathering and metamorphism change the structural layers of the rock, reduce the linkage between mineral particles and decompose the fresh rock to form clay minerals, sericite, limonite, opal and other hydrophilic minerals. Early stage of weathering and metamorphism reduce the water permeability and deteriorate the rock mechanics to the extent that it often cannot meet railway engineering requirements. For example, fresh hard granite, after weathering and metamorphism, becomes loose and fragile, ultimately turning to powder, which shows that weathering and metamorphism is an important factor directly affecting the performance of rocks.

Another example is shown in [58]. LAA tests were carried out on the parent rock material at different quarrying layers and the results are shown in Table 20. Granite[1] was the second layer of quarrying and contained coarser, more elongated particles, while the third quarrying layer produced more cubic granite[2] particles. The most superficial basalt[1] in the quarry exhibited a porous structure, while the deeper basalt[2] material exhibited higher solidity and endurance. This indicates that even with the same parent rock material from the same quarry, as mining matures, the deeper parent rock is well suited to meeting ballast standard requirements, while the superficial rock, due to weathering and geological disturbance, may have lower performance. Therefore, when selecting the parent rock for ballast, it is important to select unweathered or lightly weathered rock and to exclude the surface weathered layer.

Table 20
Parent rock material property affected by weathering (data from [58]).

Parent rock	LAA rate	Water absorption (%)	Porosity (%)	Predominant particle shape	Non-cubic particles (%)
Granite[1]	16.2%	0.20%	0.6	Cubic	13%
Granite[2]	16.3%	0.30%	0.7	Cubic	3%
Basalt[1]	23.6%	1.94%	5.73	Cubic	17%
Basalt[2]	14.3%	0.81%	2.32	Cubic	6%

4. Ballast morphology

The diameter of ballast particles varies in the range ≈10-60 mm. The particle size distribution (PSD) and shape have a significant influence on the mechanical behaviour in track conditions. Regarding ballast shape, several attempts have been made to characterise the particle shape of railway ballast. However, due to the complexity and irregularity of particle shapes, no universally recognised parameters have been established. In this section, ballast size and shape effects are discussed.

4.1. Ballast size

Ballast particle size is an important parameter in ballast standards. It can change post-extraction due to transport, handling, placement and compaction. Although sharp angularities are the first to break, some particles may crush into several small pieces, which makes changes to the PSD. Under cyclic train loading, ballast particles deteriorate further and gradually decrease in size, but even after these changes, >90% of the ballast particles remain in the original range of 10–60 mm, even after several million loading cycles. Because the median ballast particle size is around 30 mm, these particles are less likely to break compared to sizes>40 mm except by performing the tamping [25,59].

Regarding the influence of particle size on ballast layer performance, in [28,60], it was concluded that the shear angle of ballast particles decreases as the particle sizes increase. However, the ballast layer should have high porosity, so the drainage of the ballast layer should be also taken into account. The optimum PSD should provide free drainage, high strength and low settlement (initial density, shear strength and modulus of elasticity).

In [28,61], it is concluded that larger ballast particles have smaller modulus of deformation and Poisson's ratio. The average modulus increases with particle size, and at low confining pressures, the rebound modulus is almost linearly related to the average particle size. When the stress does not exceed a critical value, the smaller ballast particles have

Table 21
PSD recommended by AREMA.

Sieve size (mm)	Sieving rate (mass percentage, %) Grade A: 63.5	Grade B: 63.5	Grade C: 50.8	Grade D: 50.8
76.2	100	100	–	–
63.5	90–100	80–100	100	100
50.8	–	60–85	95–100	90–100
38.1	25–60	50–70	35–70	60–90
25.4	–	25–50	0–15	10–35
19.1	0–10	–	–	0–10
12.7	0–5	5–20	0–5	–
9.5	–	0–10	–	0–3
4.75	–	0–3	–	–
2.38	–	–	–	–

Table 22
Ballast particle size distribution on French railways.

Sieve size (mm)	Upper bound	Optimal upper bound	Optimal lower bound	Lower bound
80	100			
63	98	100		
50	80	86	100	100
40	35	40	76	80
25	0	0	5	10
14			0	0

Table 23
PSD required in British standard: aggregates for railway ballast.

Sieve size mm	Railway ballast size 31.5 mm to 50 mm Percentage passing by mass Grading category G_CRB A	Railway ballast size 31.5 mm to 63 mm G_CRB B	G_CRB C	G_CRB D	Railway ballast size 22 mm to 40 mm G_CRB E
80	100	100	100	100	–
63	100	95 to 100	95 to 100	93 to 100	–
50	70 to 99	65 to 99	55 to 99	45 to 70	100
40	30 to 65	30 to 65	25 to 75	15 to 40	90 to 100
31.5	1 to 25	1 to 25	1 to 25	0 to 7	60 to 98
22.4	0 to 3	0 to 3	0 to 3	0 to 7	15 to 60
16	–	–	–	–	0 to 15
8	–	–	–	–	0 to 2
31.5 to 50	≥50	–	–	–	–
31.5 to 63	–	≥50	≥50	≥85	–

NOTE The requirement for passing the 22.4 mm sieve applies to railway ballast sampled at the place of production.
In certain circumstances a 25 mm sieve may be used as an alternative to the 22.4 mm sieve, when a tolerance of 0 to 5 would apply.
When assessing production within a system of FPC, at least 90% of gradings, taken on different barches within a maximum period of 6 months, shall fall within the limits specified in Table 1.

Table 24
Comparison of ballast PSDs: Australian standard and Indraratna in [63,64].

Sieve size (mm)	Passing (%, by mass) Recommended by Indraratna	60	50	60 (steel sleeper)
63	100	100	–	100
53	85–100	85–100	100	95–100
37.5	50–70	20–65	90–100	35–70
26.5	20–35	0–20	20–55	15–30
19	10–20	0–5	0–15	5–15
13.2	2–10	0–2	–	0–10
9.5	0–5	–	0–5	0–1
4.75	0–2	0–1	0–1	–
1.18	–	–	–	–
0.75	–	0–1	0–1	0–1

Table 25
PSDs in Chinese standard.

Sieve size (mm)	Special grade Passing (%, mass)	Sieve size (mm)	First grade for new line Passing (%, mass)	Sieve size (mm)	First grade for existing line Passing (%, mass)
63	100	63	100	63	100
50	70–99	56	92–97	56	92–97
40	30–65	45	55–75	45	55–75
31.5	1–25	35.5	25–40	35.5	25–40
22.4	0–3	25	5–15	25	0–5
		16	0–5		

less deformation, but the final strength after compaction is lower. The larger size particles stabilise the ballast layer, while the smaller particle sizes reduce inter-particle contact stress and thus particle fragmentation.

For the PSD, the types are divided mostly into narrow PSD and wide PSD, which is quantified by the coefficient of uniformity. It is calculated as the value of the largest sieve size divided by the smallest sieve size. In [1], it was concluded that (1) widening the ballast PSD usually increases the ballast shear strength, (2) the ballast shear strength depends not only on the value of the coefficient of uniformity (Cu) but also on the average ballast size (d_{50}), and (3) increasing the average ballast size usually increases the ballast shear strength.

In [62], cyclic triaxial tests on different PSDs were performed. It was found that the cumulative deformation of uniformly PSD (Cu = 1.14) was almost twice as high as that of the wider PSD (Cu = 4.1). Further, [26] showed that the application of wider PSD instead of more uniform PSD has small influence on calculating particle morphological indices. The PSD comprised of a wider size range of particles results in strong aggregate skeleton, which enhances the resistance against single ballast particle breakage.

The ballast PSD recommended by the American Railway Engineering and Maintenance-of-Way Association (AREMA) is shown in Table 21. In all the recommended ballast PSDs, the amount of aggregate passing the No. 200 sieve (0.075 mm) should be<1%. The amount of clay and easily-crushed particles should be<0.5%. The PSD of Grade B has the coefficient of uniformity>3, which is more uniform than Grade A, C and D PSDs. The AREMA handbook recommends Grade A, C and D PSDs to be used for mainline railways, while Grade B for other types of railways.

According to the principles for the selection of ballast PSD in the EU standards, climate is the main reason for the differences in PSDs between national standards. Therefore, the EU standards recommend different PSDs according to different latitudes of railway line. The ballast PSD limits specified for French railways are shown in Table 22 as an example. In this case, ballast particles should be within the range of 16–63 mm, and particles out of this range should be<2%.

The British standard for railway ballast is shown in Table 23, where the PSDs are highly uniform. Specifically, Grade A PSD has a much smaller coefficient of uniformity (Cu = 1.4) than other ballast PSDs (also other standards in different countries).

The PSDs from the Australian standard are shown in Table 24. The recommended ballast PSD by Indraratna in [63,64] has the coefficient of uniformity in the range of 2.2–2.6, which is more uniform than the ballast gradation specified in earlier Australian standards.

The Chinese standards for ballast PSDs classify the ballast into special grade and first grade. The difference between special grade ballast and first grade ballast is the sieve sizes, as shown in Table 25. Another difference is the content of particles with size<25 mm. The special grade requires>50% of the particles to be in the size range of 31.5–50 mm,

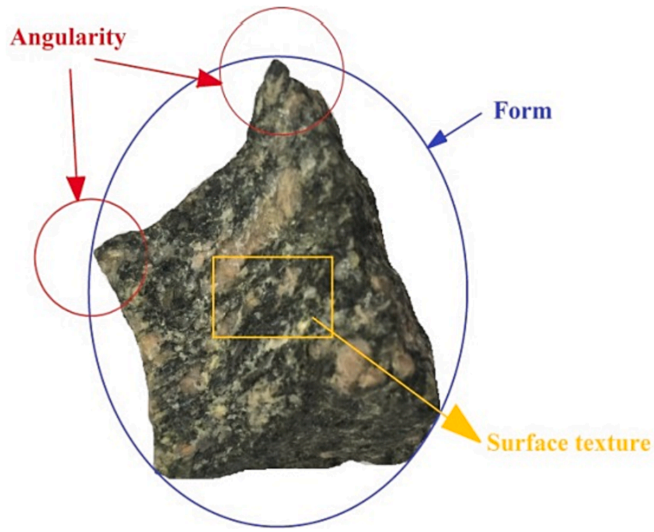


Fig. 7. Shape properties of ballast particle (figure). reproduced from [25]

while no such requirement exists for the first grade ballast. PSDs in Chinese standards, compared to the Australian, American and British ones, are narrow. For example, a maximum sieve size in America is 76.2 mm, and the minimum sieve size in Australia is 9.5 mm.

4.2. Ballast shape

Regarding ballast shape characteristics, flake and elongation are commonly mentioned in ballast standards. In research, alternative shape characteristics have been studied using high-accuracy image analysis technique or DEM modelling [65,66]. In such studies, the ballast particle shape is often classified using three properties (form, angularity and surface texture), as shown in Fig. 7.

In [58], three ballast standards (Brazil, USA and Australia) were compared to evaluate the different properties of ballast materials related to durability and shape, as shown in Table 26. From the table, it can be seen that the particle shape also has influence on the test results, which is hard to control during standardised testing.

Earlier studies have shown that particle shape influences the performance of each ballast particle and thus the ballast layer [42]. For example, in [26] effect of parent rock type, angularity and surface texture on particle degradation was studied. By considering three different parent rocks, the parent rock strength was shown to influence ballast particle angularity and surface texture. It was found that the freshly crushed basalt ballast had better angularity and surface texture, but also a greater number of flaky and elongated particles.

In [4], it was shown that form, angularity, and surface texture are critical properties that influence ballast performance and that reducing them affects ballast particle interlocking. Particle interlocking contributes to stiffness, resilience and deformation of ballast layer. Because ballast layer deformation results from particle rearrangement, particle breakage (fracture/crushing) and particle abrasion (mostly wearing of sharp corners). Specifically, due to the train loading, particle degradation (breakage and abrasion) reduces the overall resilience of ballast layer. Additionally, ballast particle movements and rotations (particle rearrangement) make ballast layer more compacted, which also contributes to the ballast layer deformation.

Most quantitative methods for ballast shape measure the longest (L), shortest (S) and intermediate (I) orthogonal dimensions and combine two or three into a dimensionless index [67]. According to ballast standards (British, Chinese, American), I/L is the elongation and S/I is the flatness (or flake, flakiness) ratio. These values are calculated for each particle and their rate (usually mass percentage) determines whether the sample consists mainly of flaky and elongated or cubic particles.

Different criteria have been used to classify the shape of the particles using different bounds in each ballast standard. Specifically, the British Standard considers a particle as flaky when the S/I is>1:1.67. The American standard gives three choices of S/I, which are 1:2, 1:3 and 1:5. The Brazilian standard uses S/I as 1:2. The elongated particles are defined differently in various standards. The British standard consider particles with I/L over 1:1.8 as elongated particles, while the American and Brazilian standards use the same rates (1:2, 1:3 and 1:5) as flakiness [58]. Chinese standards use S/I of 1:1.67 and I/L of 1:1.8, which are the same as British standard. The elongation and flakiness are often used to quantify ballast particle shape, due to their ease of use. More complex and accurate shape quantification requires more accurate tools (e.g., laser scanner [65]), which is time consuming and possibly expensive.

Particle shape is also influenced by particle size. In [67], Image Pro Plus analysis software was used to study the shape of ballast particles. The analysed particle sizes ranged from 9.5 mm to 62.5 mm. It was concluded that the larger the ballast particles had smaller S/L values, meaning the larger particles tended to be less spherical. In addition, the larger particle shapes tended to be flat, and the angularity tended to be sharper. This is in agreement with the conclusion obtained in [22,68] that larger particles generally have a lower ellipsoidness (higher angularity) than smaller particles.

In [69], the uniaxial static load test (aka unconfined compression test) was performed on single ballast particles. Results showed that the most easily crushed particles were flaky ones, and the least easily crushed particles were cubic ones.

Ballast particles with desirable shapes (e.g. high angularity), can offer superior short-term ballast layer performance, such as lateral resistance for track buckling. In [70], the effects of angularity on the mechanical performance of ballast particles were analysed and two types of ballast materials, McAbee ballast and gravel ballast were tested. The mechanical performance was presented by lateral resistance from ballast to sleeper. McAbee ballast is a rough and angular particle formed by crushed amphibole, while the gravel ballast consisted of particles with a smooth surface and three types of angularity: low angularity (original rounded gravel), intermediate angularity and relatively high angularity (crushed gravel). The results showed that the peak friction angles at the interface of sleeper bottom and ballast for McAbee ballast and gravel ballast were 33.7° and 30.7°, respectively. The lateral resistance of the gravel ballast was 9.4% lower than that of the McAbee ballast.

Table 26
Ballast properties in three international standards (Brazil, USA and Australia) [58].

Standard	LAA (%)	Sulphate Soundness (%)	Specific gravity (kg/m^3)	Water absorption (%)	Porosity (%)	Predominant particle shape	Non-cubic particles (%)
Brazil[3]	≤30.0	≤10.0	≥2500	≤0.8	≤1.5	Cubic	≤15
USA[17]	≤35.0	≤5.0	≥2600	≤1.0	–	Cubic	≤5
Australia[18]	≤25.0	–	≥2500	–	–	–	<30

Note: Brazilian ballast standard, ABNT NBR 5564. Via férrea – Lastro ferroviário – Requisitos e métodos de ensaio, Rio de Janeiro, 2011; American ballast standard, American Railway Engineering and Maintenance-of-Way Association (AREMA): Manual for Railway Engineering (MRE), Chapter 1: Roadway and Ballast, Maryland, USA, 2009; Australia ballast standard, AS 2758.7: Aggregates and rock for engineering purposes, Part 7: Railway ballast, NSW, Australia, 1996.

Table 27
Cohesion and friction angle of granite ballast particles [72].

Test series code	Number of revolutions in abrasion machine	Ballast strength properties	
		Cohesion, C, kPa	Friction angle,φ, °
TS8 (new crushed stone)	–	55	52.4
TS9	100	51	50.6
TS10	200	46	51.2
TS11	500	21	50.7
TS12	800	9	55.4

The effect of angularity and surface texture on the performance of ballast layers was studied in [71]. It showed that sharp particle corners increase the ballast dilation and restricts relative motion between contacting ballast particles, resulting in increased shear strength. This was proved by performing direct shear tests and DEM simulations of a mixture of aged and fresh ballast. Its results showed that the shear strength and friction angle of the aged and new ballast mixture decreased while the dilation increased, when the fresh ballast in the mixture was>30%.

This was also proved in [72] using triaxial tests, and the results are shown in Table 27. Specifically, the granite ballast particles after being worn were found to have lower interlocking, while the friction angle was not reduced to a significant extent. This indicates that the interlocking decreases to zero as the ballast particles approach a rounded shape, i.e. the reduction in the strength properties of the ballast.

In [39], it was concluded that surface texture is more important than ballast form or angularity in affecting track stability. Strict control of ballast particle surface texture is used in the Canadian railways, rather than direct control of ballast particle form or angularity.

Among the particle shape properties (form, angularity and surface texture), it remains unclear regarding which is the most important. For example, in [73,74], the elasticity modulus of a ballast assemblies increases with its surface roughness. In other words, the ballast layer (composed of rough-surface ballast) has high resistance to plastic deformation. This also explains the results of the tests in [42]: aged ballast does not significantly lose resistance to impact loading, but it has more plastic deformation than fresh ballast. However, the cases become more complicated when other factors are involved, e.g. porosity (bulk density). In [75], it was concluded that angularity and PSD affect the porosity achieved when considering the same compaction effort. IN particular, particles with higher angularity and PSD uniformity present higher porosity. Further, high porosity have greater scope plastic deformation due to particle rearrangement.

4.3. Ballast with multiple PSDs

Stone blowing is used to lift the sleepers and add ballast particles with smaller PSD than traditional ballast to improve sleeper support. This then results in a ballast layer with two different PSD's, where immediately after laying, the upper ballast layer consists of particles with smaller diameters, while the lower layer consists of particles with larger diameters. Studies into stoneblowing (aka pneumatic ballast injection), concluded that the size, thickness and type of the blown stones determine the ballast layer performance after maintenance [76]. Further, in [77], a mixture of stones and rubber chips was blown into the voids between sleeper and ballast bed. It showed that using the rubber chips reduced ballast layer deformation and particle degradation (breakage and abrasion).

Rather than introduce smaller PSD stones during maintenance, an alternative solution to improve sleeper support is the creation of a dual-layer ballast during construction/renewal to reduce the occurrence of hanging sleepers. For example, [9] proposed a two-layered ballast prototype, which where the crib ballast around the sleepers was replaced with smaller size ballast. By this means, the voids between sleeper bottom and ballast bed (hanging sleeper) can be filled by migrating smaller particles when the voids become large. Model and full scale laboratory tests were performed, by which the ability of two-layered ballast was validated. Further, [78], studied the sleeper to ballast interface considering two-layered ballast. It showed that two-layered ballast increased the contact number and area of sleeper-ballast, meaning the ballast layer could provide better support to the sleeper. However, only the contact area was measured in this study, and no detailed numbers or values were given.

Alternatively [79] studied stress distributions in the ballast layer and plastic settlement during cyclic loading via full scale laboratory tests, as shown in Fig. 8. The long-term performance of two-layered ballast was compared with the standard ballast layer. Results showed that the two-layer ballast had over two times lower initial settlement, but for the long-term performance, it produced 2.5 times higher settlement accumulation.

5. Ballast petrography

The studies [80,81] stated the most suitable parent rock materials for ballast are igneous and metamorphic, and therefore ballast is usually composed of the following minerals: rhyolite, dolomite, basalt, gneiss, quartzite and granite. The petrographic characteristics of the rock, such as micro-fractures, mineral grain size and soft mineral content, affect the mechanical and mechanical properties of ballast [16]. Rocks of the same name often show different test results due to differences in their respective macro and micro petrographic characteristics.

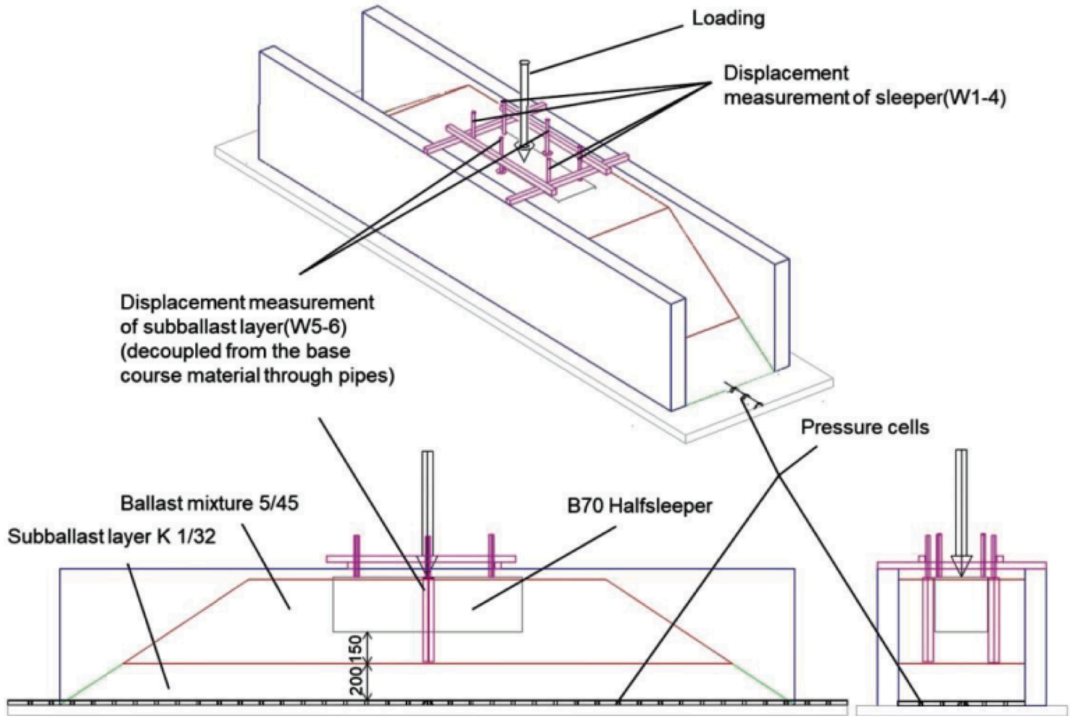
The mineral grain size and soft mineral content have effects on the mechanical strength of ballast, however their correlation with the parent rock properties as well as ballast performance is still unclear. This can lead to unknown variables and various studies showing differing correlations related to ballast performance. Further, the factors influencing ballast performance are numerous, and therefore this section discusses the importance of quantifying rock petrographic characteristics [16].

Firstly, regarding minerals, although there are a large number of types of mineral in existence, there are only approximately a dozen types that can make up rocks. Table 28 shows the main rock-forming minerals, with hardness>5 being called high-hardness minerals and those<5 low-hardness minerals. Rocks that are predominantly composed of high hardness minerals are generally "hard rocks" and vice versa for "soft rocks". In general, the mechanical properties of fresh rock, such as abrasion rate, impact toughness, abrasion hardness and crushing rate, are largely determined by its mineral composition. This was proved in [82].

Even if the material is from the same parent rock, the particle size of the component minerals has an impact on the performance of the ballast layer. In [51], experiments were performed on small and large mineral size basalt, and the results show that the small mineral size basalt has lower Los Angeles abrasion rate (proving better abrasion resistance). In addition, small mineral size basalt showed greater magnesium sulphate soundness values, suggesting that the small mineral size basalt is more stable under sulphate attack. This is because small size mineral grains can more firmly bond their neighbouring mineral grains. Therefore, the ballast material should be better to select the rock with small size of mineral grains [51].

Another factor that affects ballast performance is mineral form. The best mineral form is granular, and some high hardness minerals are granular minerals, such as quartz and feldspar. Columnar minerals are the next best, while scaly and fibrous minerals are the worst. The mechanical properties of rocks with a homogeneous structure are generally higher than those with a heterogeneous structure. Preferable rock structures have small mineral sizes, similar morphology (size and shape), high mineral interlock and a high content of granular minerals.

For example, in [17], several rock types with different mineral compositions were compared on mesoscopic scale, as shown in Fig. 9.



(a)

(b)

Fig. 8. Schematic view and laboratory test setup (top: double layer ballast, bottom: standard ballast layer): (a) Schematic view of test setup; (b) test setup (figure). reproduced from [79]

Details of their mineral composition are given in Table 29. This study was on correlating the LAA rate with different mineral composition. Results show mineral composition has a considerable impact on the LAA rates, however, the influence of particle morphology (angularity, surface texture) is relatively small.Fig. 10. Fig. 11.

Rocks such as granite, which are composed mainly of high hardness minerals (high hardness mineral content>80–90), have strong ballast performance. High hardness minerals include quartz, plagioclase,

Table 28
Hardness of the main component rock minerals.

Mineral	hardness	Mineral	hardness
Quartz	7	Sericite	2.5–3
Plagioclase	6–6.5	Black mica	2–3
Potassium feldspar	6	White mica	2.5–3
Common hornblende	5.5–6	Clay minerals	1–2.5
Ordinary pyroxene	5–6	Chlorite	2–2.5
Olivine	6.5–7	Garnet	6.5–7.5
Green cordite	6.5	Serpentine	2.5–3
Calcite	3	Talc	1
Dolomite	3.5–4		

Table 29
Mineral composition of seven rock types (modified after [17]).

Rock type	Code	Parent rock class	Mineral composition
Basalt	2	Igneous	Pyroxene, foids, magnetite
Granite	3A	Igneous	Quartz, feldspar, amphibole, biotite, garnet
Granite	3B	Igneous	Quartz, feldspar, amphibole, biotite
Dunite	4A	Igneous	Serpentine, olivine, amphibole
Dunite	4B	Igneous	Serpentine, olivine, amphibole, chlorite
Granulite	10A	Metamorphic	Quartz, feldspar, biotite, garnet
Granulite	10B	Metamorphic	Quartz, feldspar, biotite, garnet

potassium feldspar, hornblende, pyroxene, olivine and garnet. On the contrary, rocks consisting mainly of calcite, dolomite, clay minerals, mica and other low hardness minerals generally less suited for railway application. Crushed rocks containing chert and dolomite are often considered to constitute poor quality ballast, and for example are not permitted on normal railway lines in China. Another example is limestone and dolomite aggregates, which should not be used with concrete sleepers, as stipulated by the US Railway Engineering Board [83].

Table 30 shows typical evaluation methods for the mineral compositions and mineral properties. However, studies correlating these properties with ballast layer performance are limited.

In [46], the relationship between the mineral content of quartz and feldspar and the LAA of graded aggregates was investigated. From the figure, it can be observed that the quartz percentage plays key role on the LAA rate, which means a high percentage of quartz leads to lower LAA rate. This was also demonstrated by [17], and therefore mineral composition may act as a useful evaluation parameter.

In [84], a range of mineral compositions and rock properties were studied, as shown in Table 31. However, it was found difficult to obtain strong correlations between mechanical tests and mineral compositions. This is because some rocks that have high strength may have small mineral grain size but also with amount of micro-cracks. The micro-cracks lead to easy particle crush and produce more particle abrasion. Therefore, there is an opportunity to add average mineral grain size and micro-crack evaluation to standards.

6. New ballast materials and environmental impacts

6.1. New ballast materials

Conventional ballasted track accounts for a high proportion of global railway tracks (approx. 90%) [1]. Considering the global strategy of low carbon, carbon neutral and circular economies, maximising ballasted track lifespans instead of replacing/building new tracks is important. For example, [85] performed a life cycle assessment of railway infrastructure. It analysed the Spanish high-speed railway network using standard ISO 14040, by comparing conventional ballasted track and slab track. The results showed that after 50–60 years of service life, the conventional ballasted track had lower environmental impact.

There have been a variety of advancements in ballast technology aiming to increase the lifespan and performance (Table 34). For example, it has been shown that if no>30% of the ballast is mixed with new ballast, ballast layer performance can still be maintained [71]. Further, ballast waste can be used to help pave roads when mixed with asphalt [86].

Rather than reusing railway industry waste, waste products from other industries can also be recycled for use on railways. For example, steel slag from steel production is an abundant by-product material in the USA, China, Australia and some European countries [87,91]. [92] presents a summary of the physical properties of slag materials and potential applications related to railway ballast. However, considering railway signalling and electrical conductivity issues, to-date slag has mostly been confined to research (e.g. [91]). However, there have been studies on mixing waste rubber and slag to improve its mechanical properties [93], and scaled tests comparing the mechanical properties of steel slag with those of conventional crushed ballast [94]. Results showed that on heavy haul railways, steel slag ballast has a higher modulus of elasticity, less permanent deformation under high intensive train loadings and a higher shear strength. This is similar to the conclusion reached by Kaya [95] and Koh [96] that steel slag is able to replace conventional crushed rock ballast in terms of mechanical properties. Steel slag physical properties can be found in Table 32.

It has also been shown that high density slag can improve track stability, increasing the lateral resistance of the ballast layer by 27% [97] and the vertical stiffness by 64% [98]. It can also reduce the probability of ballast flight on high-speed railways [99].

Delgado et al [100] compared electrical arc furnace steel slag ballast and conventional granite ballast, both with similar MDA rate, using cyclic triaxial tests. The authors compared the morphology difference of steel slag ballast and granite ballast. Results show there were no significant differences in sphericity and surface texture. The steel slag had greater angularity and shear strength compared to the granite ballast. This also explains the difference in performance of the two types of ballast under triaxial cyclic loading. Specifically, the results of cyclic loading tests showed that the furnace steel slag ballast exhibited higher

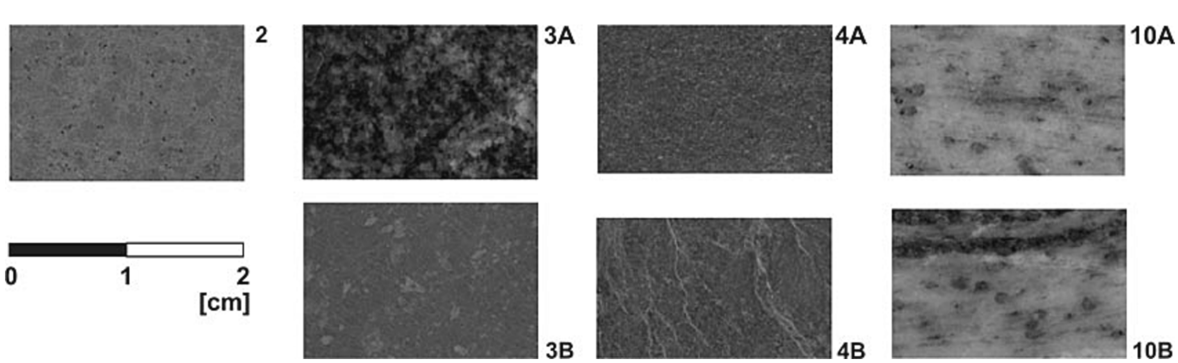


Fig. 9. Seven kinds of rock with different mineral compositions (figure). reproduced from [17]

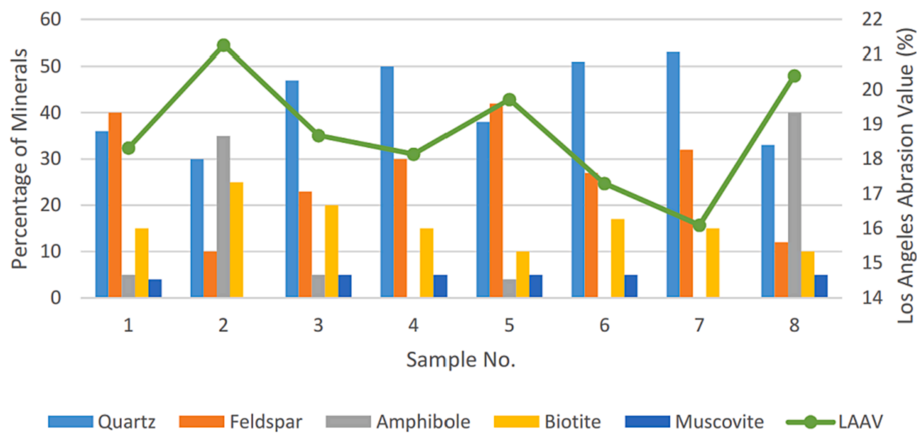


Fig. 10. Relationship between mineral parentage and LAA rate (figure).
reproduced from [46]

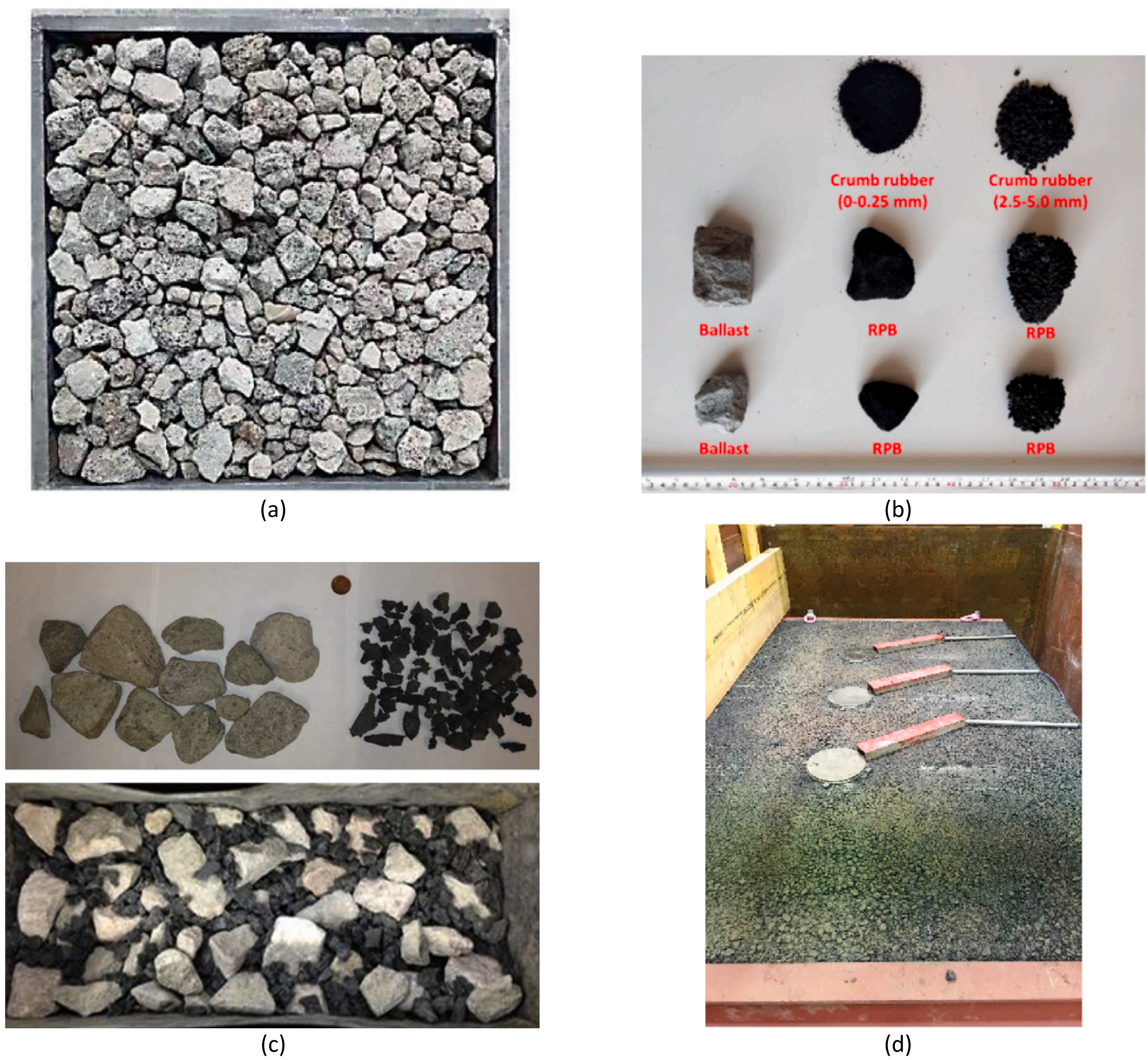


Fig. 11. Waste materials applied as railway ballast: (a) Steel slag in direct shear test box; (b) Rubber-coated ballast or Neoballast; (c) Mixture of ballast and rubber chips; (d) Asphalt ballast layer (figure).
reproduced from [87–90]

Table 30
Evaluation methods for aggregates' mineral properties [16].

Property	Evaluation method
Water absorption	Porosity
Specific density	Weight per solid volume unit
Microscopy	Micro-cracks
Microscopy	Mineral grain size distribution
Microscopy	Mineral grain size
Microscopy	Mineral distribution
Image analysis	Surface texture
X-ray diffraction	Semi-quantitative to mineral identification and distribution
Coulter	Sieve analysis (fines)

modulus of elasticity values compared to the granite ballast. In addition, regarding the loss of stiffness after long-term deformation, the granite lost stiffness more rapidly than the steel slag ballast. These results were in agreement with the results obtained through finite element simulations: the steel slag ballasted track showed lower track vertical displacement than that of granite ballast.

In [97], the tested properties were compared as shown in Table 33. From the table, it can be seen that the steel slag had higher strength than limestone ballast. In addition, it has higher unit weight, which can prevent the ballast flight and provide higher track stability.

Another waste material with potential use as ballast is construction and demolition waste. These kinds of material have been noted to be used as fillers for the ballast layer, and a large number of field tests have been conducted [101–104]. Youventharan et al [104] proposed mixing Concrete Debris or bottom ash with ballast (neither the concrete debris nor the bottom ash met the AREMA target of 35% for LAA rate). The results showed that when ballast is mixed with concrete debris, the Aggregate Crushing Value loss was almost halved, by which the value meets the requirement in the ballast standard.

Alternatively, rubber chips (e.g. recycled from car tyres) have been tested in the ballast layer, with the aim of improving mechanical properties. This has been shown to slow down ballast abrasion and breakage [105–108]. [109] firstly proposed to use rubber chips to reduce vibration and noise transmitted from railway to nearby buildings, particularly, the rubber chips were added in the foundation. Afterwards [110–112] studied the vibration reduction of the sub-ballast layer mixed with rubber chips. Particularly, mixture of rubber chips, steel furnace slag and coal wash as sub-ballast layer was studied in [113].

For the ballast layer, the rubber chips were used in ballast layer as elastic particles to reduce ballast degradation in [90]. Afterwards, more laboratory tests, including direct shear test and ballast box test, were performed to obtain the optimal percentage as 10%of rubber chips-

Table 32
Physical properties of three kinds of steel slag [44].

Properties	Blast furnace slag	Steel furnace slag	Electric arc furnace slag
Bulk density (t/m^3)	1.20	1.70	1.70
Particle dry density (t/m^3)	2.45–2.55	3.30–3.40	3.30
Dry strength (kN)	85–100	275	250
Wet strength (kN)	65–90	230–300	240–300
Wet/Dry variation (%)	10–20	5–20	5–15
Water absorption (%)	4–7	1–2 (coarse) 2–4 (fine)	1–2 (coarse) 2–4 (fine)
Polish aggregate friction value	50	58–63	58–63
Sodium sulphate soundness (%)	<1	<4	<4

Table 33
Comparison of limestone ballast and steel slag ballast [97].

Feature	Unit	Limestone ballast	Steel slag ballast	Standard test method
Water absorption	%	0.7	0.9	ASTM C127
Granular unit weight	gr/cm^3	2.63	3	ASTM C127
Sodium sulphate durability	%	0.23	0.1	ASTM C88
Los angles abrasion loss	%	25	14	ASTM C535
Micro-Deval abrasion loss	%	12.4	5.6	ASTM C6928
Peak mobilised angle of internal friction	degree	43.16	46.94	ASTM C3080

Table 31
Mineral compositions and corresponding rock property evaluation (modified after [84]).

Deposit no.08115-	Quarry	Geologiacal name	Minerals Q	F	K	B	M	A	E	Chl	Car	Grain size mm interval
1	Steinkjer	Meta sandstone,meta Greywacke,quartzite	48	18	15		18					0.1–1.5
2	Meratfåsen	Greenstone	5	32	5		6	8	9	29	6	0.01–0.2
3	Lauvåsen	Meta greywacke-argillite	14	23	3		26		12	25	9	0.05–0.5
4	Vassfjell	Meta gabbro,catalasite	1	18	6			41		18	4	0.1–5
6	Aplitt	Catalasite,crush breccia,granite	54	15	29					2		0.05–2.5
11	Lørenskog	Mylonite,gneiss,gabbro	28	48	6	4		14				0.05–1
12	Freste	Monzonite	7	59	23			7		2	1	7–10
23	Rombak	Mica gneiss	46	21	2	10	17			3	1	0.01–0.4
26	Sefrivatn	Gneiss granitic	24	42	27	2		2		2	1	0.1–0.5

Aggregate deposits with geologic names and mineralogical compositions.Minerals:Q(quartiz),F(plagioclase),K(k-feldspar),B(biotite),M(muscovite),A(amphibole),E(e[idote),Chl (chlorite),Car(carbonate).

Deposit nr	Quarry name	LAAdry	LAAwet	Micro Deval	SI20	Specific Density	Surface Texture Index	LAA 10-14mm	Mineral grain size D50mm
1	Steinkjer	16.9	14.4	4.8	18.2	2.71	2.00	20.9	0.138
2	Meratfåsen	12.4	18.3	11.2	7.1	2.95	0.88	17.5	0.088
3	Lauvåsen	25.7	26.7	15.7	13.5	2.77	0.90	19.2	0.119
4	Vassfjell	13.3	23.4	8.7	7.3	3.08	1.33	14.4	0.333
6	Aplitt	21.4	20.7	3.4	13.4	2.67	1.89	21.3	0.487
11	Lørenskog	12.8	16.3	6.0	14.7	2.91	1.56	20.3	0.203
12	Freste	21.8	21.9	6.6	13.9	2.73	1.10	22.5	3.815
23	Rombak	13.7	20.2	9.5	11.7	2.78	1.40	18.1	0.180
26	Sefrivatn	24.4	19.3	4.6	11.2	2.67	2.27	24.9	0.263

The rock characterisation is performed on fraction 31.5-50mm

Table 34
New ballast materials.

Material	Layer	Evaluation
Steel slag [100,102,103]	Applied as a ballast layer	The lateral resistance of the track with steel slag ballast increased by 27% compared to that of the limestone ballast [102]; the track vertical modulus of elasticity of the track with the steel slag ballast was 1.64 times higher than that of the limestone ballast. The contact pressure between the sleeper and ballast in the limestone ballast was almost double that between the steel slag ballast and sleeper [103].
Steel slag and crushed rocks [87]	Steel slag-ballast mixture ballast layer	By mixing the steel slag by 50% (or lower) with crushed rocks, the slag-rock mixture is guaranteed to meet the standard for special class ballast in terms of abrasion resistance. The shear strength of the slag-rock ballast layer is significantly improved compared to pure steel slag ballast layer.
Rubber chips [89,90,106,107,114,121]	Damping aggregates in ballast layer	The literature [106] proposed that stone-blowing can blow the mixing of gravel and rubber chips at the sleeper-ballast voids. This can improve the maintenance quality, by reducing ballast layer settlement and deterioration, improving the mechanical properties of the ballast layer and extending the service life of the railway track. The literature [90,114,121] showed that the optimum ratio of rubber chips mixed with ballast is 10% (mass or volume ratio). Studies in [107,122] investigated the use of waste rubber chips to modify the high stiffness and poor elasticity of the ballast layer in wind-blow sand areas. The ballast deterioration was effectively reduced by the optimum 5–10 mm sizes of rubber chips. The optimum volume ratio of rubber chips that mixed with sand and ballast is 30%.
	Bonded to ballast particles	The abrasion resistance of the rubber-coated ballast is improved by about 60%, compared to the ballast without coated rubber chips. 0.0–0.25 mm rubber chips to coat the ballast has better deterioration resistance and shear resistance than 2.5–5 mm rubber chips.
Steel slag mixed with rubber chips [93]	Ballast layer	When the added percentage of rubber chips exceeded 10%, the ballast layer settlement reached 25 mm in a short period of time, which was not satisfactory. This is in agreement with the observations made in [114]. Also the settlement of the steel slag ballast layer mixed with 5% rubber chips became smaller, because the rubber chips filled in the void spaces between the ballast particles. This leads to the mixture density increased and the inter-particle movements in the vertical direction were reduced. By increasing the percentage of rubber chips, the damping of the samples increases, while their dynamic stiffness decreases. A comparative analysis led to the conclusion that 10% by weight of rubber particles (size: 20–60 mm) was the optimum mixing ratio.
Asphalt [120]	Ballast layer or sub-ballast layer	The use of asphalt ballast layer can better modify the ballast layer stiffness, by bonding the discrete ballast into a form of track between slab track and ballasted track. The asphalt can be recycled and decomposed after heating, making it easier to maintain and repair. Currently, only a few countries, such as the Austrian railways, utilise asphalt sub-ballast layer on their railway lines. There are still many practical problems to be solved in large-scale applications, such as repairing damage to the asphalt bed.
Polyethylene fibres [123,124]	ballast fibre composite	Tests have shown that the introduction of polyurethane fibres can enhance the shear resistance of fine sand. On this basis the fibrous material was mixed with ballast and the results showed that when narrow fibres were used, the fibre-reinforced ballast reduced the settlement by approximately 25%. This is due to the fact that the use of fibres in granular materials reduces the lateral expansion of the mixture (smaller principal strains) and mobilises a higher stress ratio.
Polyurethane, cement and geopolymer [125–128]	Gluing ballasted track into slab tracks	The effects after applying these binders are similar to asphalt. The differences are costs, working principle and installation. Geopolymer was proposed in recent decades for low-carbon footprint, and it is promising after solving some main problems, such as thermal expansion and contraction. Another issue is that the glued ballast layer may suffer rapid degradation due to the fouling in the ballast layer.

Table 35
Advantages and disadvantages of new ballast materials.

New ballast materials	Advantages	Disadvantages
Steel slag	Disposal of waste material; high strength; suitable for steel sleeper; high angularity; ballast flight prevention; low degradation; high stiffness; low permanent deformation; low carbon	Volume expansion; leaching of heavy metals; signalling interference; incomplete standard; difficulty in quality control; heavy track; high maintenance cost
Rubber chips	Disposal of waste material; degradation reduction; suitable for steel sleeper; noise reduction; material circularity; long service life; light weight; stiffness modification; replacement of other rubber products; low cost	Drainage interference; potential contamination; low resilience; performance uncertainties; expensive binder for Neoballast; interference in ballast-ballast contact; movement uncertain in ballast layer
Asphalt	Low track geometry degradation; high capacity for high speed; aggregate degradation reduction; waterproof	High maintenance cost; high cost; difficult maintenance; temperature deformation; long-term creep control

Table 36
Contribution to the total externality of each impact category [138].

Impact categories	Percentage of contribution to the externality cost			
	Cons/Renw TB	Cons/Renw BSB	Tamping TB	Tamping BSB
Climate change	3.38%	3.30%	1.69%	2.23%
Fossil depletion	6.72%	7.70%	14.53%	23.71%
Freshwater ecotoxicity	0.39%	0.41%	0.47%	0.72%
Freshwater eutrophication	0.00%	0.00%	0.00%	0.00%
Human toxicity	1.02%	1.09%	1.54%	2.17%
Marine ecotoxicity	0.33%	0.38%	0.72%	1.15%
Marine eutrophication	0.03%	0.03%	0.02%	0.02%
Metal depletion	0.00%	0.00%	0.00%	0.00%
Ozone depletion	0.00%	0.00%	0.00%	0.00%
Particulate matter formation	0.71%	0.70%	0.40%	0.61%
Terrestrial acidification	0.51%	0.51%	0.37%	0.55%
Terrestrial ecotoxicity	0.02%	0.02%	0.02%	0.02%
Urban land occupation	0.00%	0.00%	0.00%	0.00%
Water depletion	78.66%	76.94%	67.08%	48.40%
Primary energy demand	8.21%	8.91%	13.16%	20.43%

ballast mixture in [114]. [115] used discrete element method (DEM) modelling to study the contact forces of the mixture. Results showed that the ballast breakage was reduced through alleviating large contact forces (over 250 kN). The rubber chips were applied in the field track [116] as well as the track in some special areas, such as the bridge and desert area [107,117], and the dynamic performance of ballast layer was studied with impact loading tests or cyclic loading tests. Particularly, in [118], the drainage of ballast-CR mixture was studied, and the factors were considered, including the CR size and percentage. This study proved that<30% percentage CR (by volume) can still have acceptable drainage. In [119] a coupled model consisting vehicle, ballasted track and subgrade was used to study the dynamic performance of the whole train-track-subgrade system, whose results showed that applying rubber chips have small effect on wheel-rail interaction and vehicle dynamic responses.

Researchers have also studied the use of asphalt (and other binders) to bond the discrete ballast layer into a monolithic track (similar to slab track) [120], including a sub-ballast layer or ballast layer.

Using novel ballast materials has advantages and disadvantages compared to conventional ballast, which are summarised in Table 35.

6.2. Environmental impacts

Some studies have investigated the possibility of replacing natural aggregates with recycled ones, comparing their properties and assessing their impact on the final product [129–132]. In most cases the environmental impacts were considered in limited depth, however some studies have been performed to assess the environmental aspects of recycled aggregates [133–135].

6.2.1. Recycled ballast

Environmental pollution from ballast waste on Australian coal lines was studied [136], and found that ballast renewal/cleaning should be taken approximately on 152 km of standard railway track each year. An average of 30% ballast is called waste because it is not suitable for reuse in the track. Therefore circa 200 k cubic metres of waste ballast is discarded along the railway line each year.

Fouled ballast often contains coal dust and fine soil which pollutes water through rainfall runoff. Coal dust and soil particles can be suspended in the water, which increases the turbidity of rivers. It also slows down the process of photosynthesis by limiting the spread of light through the water. This have a negative impact on the aquatic ecosystems.

Maintaining ballast track geometry produces ballast waste. Therefore, it is important to clean and reuse as much of the waste ballast as possible. This can be done by sieving the waste ballast, and the ballast particles with appropriate size (i.e. 30–63 mm) cleaned and inserted back into the track. Particles smaller than 30 mm are discarded because they are not suitable for re-use in track.

An example of this is a High Output Ballast Cleaner System that filters ballast particles in the field. The fouled/degraded ballast particles are removed and stored in wagons for another purpose. At aggregates yards, ballast washers are mounted on the system, which decontaminates the ballast particles.

6.2.2. CO_2 emission

Recycled ballast used for making cement was studied in [137]. The International Energy Agency has proposed a CO_2 reduction plan, from 2 Gt to 1.55 Gt in 2050. In the years of maximum cement production (55 million tonnes), the cement industry used up to 5.7 million tonnes of different products and industrial waste as additives (electric arc furnace slag, fly ash, etc.). The clinker consumption was halved to reduce carbon emissions as well as production costs. Therefore, it was proposed to use recycled ballast for the production of cement. The ionic mobility along the cement pores was studied using CT Scanning, by which the performance of cement with recycled ballast was assessed. It was concluded that the cement with 10% recycled ballast was the optimal percentage.

6.2.3. Asphalt

Bitumen Stabilised ballast (BSB) has shown lower settlement than conventional ballasted track, which leads to longer tamping maintenance intervals. The BSB also reduces fouling generation due to low ballast degradation rate, and has a lower ballast breakage rate. Despite the slight increase in construction costs, BSB appears to have some advantages compared to conventional ballast over 40–60 years. Although BSB has these advantages, it can also have a negative impact on fossil energy depletion, freshwater eco-toxicity, marine eco-toxicity and initial energy consumption during the initial construction and tamping period, as shown in Table 36.

6.2.4. Steel slag

[139] reviewed steel slag as railway ballast and it stressed that one main problem of using steel slag as ballast is the leaching of heavy metals, which could cause environmental issues. The metals include Chromium, Vanadium, Molybdenum, Zinc, Lead, Barium, and Nickel. Measuring the hazardous elements (e.g., heavy metals) in steel slag is necessary. For example, in [140], it was reported that the leakage of heavy metals in steel slag when washed by water can meet the requirement by Environmental Protection Agency (EPA). Leachate concentration is dependent on the type of steel slag meaning it is necessary to propose a means of treating steel slag to prevent hazardous element leakage. For example, in [141] silicon resin was applied to prevent heavy metal leakage.

Natural ballast quarrying procedures generate large amounts of CO_2. [142] reported that the CO_2 emitted producing quarried aggregates and steel slag was about 8.47 and 3.09 kg/ton, respectively, meaning natural aggregate is 2.74 times higher than steel slag. In addition, [143] reported that using steel slag can reduce the cost of ballast by 25.3%.

7. Conclusions

This paper has five parts: ballast materials, ballast morphology, ballast parent rock types, petrographic characteristics and new ballast materials. In the first part, ballast terminology, its history and development were summarised. In addition, the ballast material selection methods in various countries and ballast material testing methods were compared. In the second part, the parent rock that has been used to produce ballast was introduced, e.g., the formation of different rocks and the influence of parent rock types on ballast resistance to degradation. In the third part, the effects of ballast morphology on ballast performance was discussed, according to the guidelines in ballast standards. In the fourth part, the mineral compositions of different types of rock were explained, based on which their influences on the ballast material performance was discussed. In the fifth part, new ballast materials are discussed for replacing current crushed rock ballast. The following conclusions are drawn.

Ballast material qualification: There is opportunity to improve the test methods for assessing, testing and quantifying ballast performance under complex field conditions. To qualify ballast by simulating real ballast degradation process in the field is challenging but has potential benefits. The current test methods for ballast performance are intended to provide a realistic prediction of ballast degradation in the field as it is exposed to environmental influences. However, studies have shown that there is a weak relationship between ballast LAA rate and its service life. Current tests cannot simulate the multi-scale, multi-physical field conditions typically experienced by railway ballast. In most cases, only water effects are considered. However, the field conditions involve complex environmental conditions (e.g., diverse ballast-sleeper interaction, impact loading, etc.).

Ballast parent rock: Different types of ballast parental rock can be used depending on the expected railway climate. For example, limestone can be used as ballast in the desert but not in areas with higher precipitation. Further, mixtures of limestone and other types of ballast (e.g. high-density steel slag) on occasion may help overcome some of limestone's disadvantages.

Ballast parental rock can be adapted to local needs, for example in France, where the ballast standard can be relaxed depending upon the railway's needs. Similarly in China if there is a shortage of high quality ballast, then 'first' class ballast can be used instead of 'special' class ballast. Only limited requirements for ballast density are specified in ballast standards, and minimal testing methods are recommended to measure the bulk density of ballast layers. In other words, there are still limited methods to determine the ballast layer overall density in a fast and accurate manner without damaging the ballast layer. Ground penetrating radar is a promising technology to fulfil this aim, however improvements are needed regarding image analysis means and efficiency.

Ballast size and shape: It is common to describe ballast morphology using PSD and elongated and flaky particle mass percentage to quantify ballast size and shape. However these measures cannot accurately reflect the short-term or long-term performance of in-service ballast layers. Therefore there is opportunity for more accurate metrics to be studied to describe particle size and shape. This could involve developing new correlations between universally recognised ballast parameters, complex irregular particle shapes and ballast layer performance.

Petrographic characteristics: Petrographic analysis can give valuable information about the mineral composition of ballast. There are opportunities to explore the effect of petrography on in-service ballast performance (e.g., degradation resistance) by correlating mineral characteristics with lab test results and ballast standards.

New ballast materials: Current ballast standards have mixed details regarding new ballast materials. For example, in Chinese standards, there are minimal specifications for new ballast materials, including recycled ballast. In comparison, in EU ballast standard (NEN-EN 13450–1:2021) recycled and manufactured ballast (mainly steel slag) are discussed. However, specifications are limited regarding differing ballast materials (made from different types of parent rocks) and regarding varying field conditions (desert area, rainy area, soft subgrade, etc.).

Future research directions: There have been limited studies on the maintainability of differing ballast types (especially new ballast materials) when concerning different tamping techniques, such as vertical and side tamping [11,59]. For example, even though studies have analysed tamping effects on ballast degradation, only one type of ballast material was used. The resistance of different ballast materials to the degradation caused by tamping and stabilisation can vary, and presents a promising research direction for the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Table A1
Comparison of LAA test requirement in different standards.

Sample Size (mm)	TB/T 2140.2–2018 Chinese standard		Sample Size (mm)	NS-EN 13,450 British standard	Sample Size (mm)	ASTM C131 [40]				Sample Size (mm)	ASTM C535[41]		
	Ballast (kg)	Sub-ballast (kg)		Ballast (kg)		A	B	C	D		1	2	3
10–16		2500 ± 10	31.5–40	5000 ± 50	25.0–37.5	1250 ± 25				63–75	2500 ± 50		
					19–25.0	1250 ± 25				50–63	2500 ± 50		
16–20		2500 ± 10			12.5–19	1250 ± 10	2500 ± 10			37.5–50	5000 ± 50	5000 ± 50	
					9.5–12.5	1250 ± 10	2500 ± 10			25–37.5		5000 ± 50	5000 ± 25
20–25	5000 ± 25		40–50	5000 ± 50	6.3–9.5			2500 ± 10		19–25			5000 ± 25
					4.75–6.3			2500 ± 10					
25–40	5000 ± 25				2.36–4.75				5000 ± 10				
Total mass	10000 ± 50	5000 ± 50		10000 ± 100		5000 ± 10	5000 ± 10	5000 ± 10	5000 ± 10		10000 ± 100	10000 ± 75	10000 ± 50
No. of steel balls	12	8		12		12	12	12	12		11	8	6
Mass of steel balls	5000 ± 25	3300 ± 20		5210 ± 90		5000 ± 25	5000 ± 25	5000 ± 25	5000 ± 25		4584 ± 25	3330 ± 20	2500 ± 15
Rotation speed r/min	31–33			33		30–33					30–33		
Revolution No.	1000	500		1000		1000					1000		
Moisture	105–110 °C dry 4 h			1. Dry to constant weight 2. Dip in water 24 h-7d		105–110 °C dry 4 h					105–110 °C dry 4 h		
Fine sieve size (mm)	1.7			1.6		1.7					1.7		
Allowable error (%)	≤2				Repeat test result deviation (same tester)	No>5.7% of the average				Repeat test result deviation	No>7.6% of the average		
					Repeat test result deviation (different labs)	No>12.7% of the average				Repeat test result deviation	No>11.8% above average		
Maximum LAA rate	Special grade ballast	Grade I ballast				Granite	Trap rock	Quartzite	Limestone	Dolomite			
	18	27				< 35	< 30	< 25	< 25	< 25			

Table A2
Physical and mechanical properties of 32 rocks [43].

	Sample name	SH	UVW (g/cm3)	AP (%)	UCS (MPa)	TS (MPa)	PL (MPa)	LAA (%)
Sediamentary	Hazar pink	51.0	2.67	1.23	110.30	8.13	6.66	22.50
	Elaszig cream	36.0	2.51	5.15	58.40	4.75	2.65	41.20
	Daisy beige	67.0	2.69	1.29	126.80	10.38	6.82	21.20
	Petrileum green	66.0	2.66	1.20	82.20	7.66	4.77	23.50
	Black pearl	60.0	2.69	0.20	108.40	8.45	5.07	20.50
	Hazar beige	55.0	2.69	0.36	61.40	5065	2.67	30.30
	Cermik beige	50.0	2.65	2.08	76.90	6.58	3.01	29.60
	Yesilova beige	56.0	2.66	0.30	70.50	6.95	4.65	26.50
	Sivrhisar beige 1	62.0	2.70	0.22	80.00	7.05	5.20	25.70
	Sivrhisar beige 2	58.0	2.69	0.22	68.00	6.09	3.70	28.10
	Diyarbakir beige	45.8	2.69	0.46	75.20	6.20	3.61	24.30
	Number of data	11	11	11	11	11	11	11
	Minimum	36.0	2.51	0.20	58.40	4.75	2.61	20.50
	Maximum	67.0	2.70	5.15	126.80	10.38	6.82	41.20
	Average	55.2	2.66	1.16	83.46	7.15	4.43	26.67
	Standard deviation	9.1	0.05	1.46	22.06	1.51	1.47	5.80
Metamorphic	Usak white	47.0	2.70	0.16	69.00	5.25	3.51	25.90
	Kozagac white	40.0	2.60	0.32	42.00	4.18	2.55	36.30
	Milas lilac	46.0	2.63	0.36	55.00	4.95	3.85	26.50
	Afyon cream	46.0	2.71	0.20	64.00	6.21	3.62	25.20
	Afyon vilet	53.7	2.70	0.17	84.19	7.44	4.67	22.60
	Kutahya green	48.9	2.70	0.20	75.53	7.69	4.53	23.20
	Afyon sugar	49.5	2.70	0.16	58.13	6.33	2.38	31.30
	Kutahya violet	50.3	2.69	0.35	63.49	6.84	3.60	24.70
	Afyon white	40.4	2.69	0.25	46.26	5.69	2.53	32.20
	Afyon violet 2	43.3	2.69	0.41	46.33	5.39	2.90	31.30
	Kutahya green 2	43.6	2.69	0.35	55.15	5.23	3.25	28.20
	Number of data	11	11	11	11	11	11	11
	Minimum	40.0	2.60	0.16	42.00	4.18	2.38	22.60
	Maximum	53.7	2.71	0.41	84.19	7.69	4.67	36.30
	Average	46.2	2.68	0.27	59.92	5.93	3.40	27.95
	Standard deviation	4.2	0.03	0.09	12.99	1.08	0.77	4.31
Igneous	Andesite 1	41.0	2.10	4.97	62.50	5.05	6.10	18.90
	Andesite 2	65.0	2.42	3.10	82.50	9.55	8.30	16.10
	Andesite 3	63.0	2.39	3.59	81.30	8.86	7.54	16.70
	Andesite 4	43.7	2.15	4.43	71.30	6.15	7.10	18.00
	Andesite 5	61.4	2.40	3.53	88.70	8.82	8.40	16.50
	Andesite 6	66.7	2.45	3.16	81.50	9.25	8.50	15.90
	Andesite 7	62.5	2.41	3.35	82.10	9.20	7.84	16.00
	Andesite 8	59.3	2.40	3.55	85.10	8.95	8.50	15.40
	Andesite 9	61.2	2.37	3.60	88.40	9.10	8.40	16.20
	Andesite 10	43.0	2.18	4.70	61.50	5.53	6.58	18.50
	Number of data	10	10	10	10	10	10	10
	Minimum	41.0	2.10	3.10	61.50	5.05	6.10	15.40
	Maximum	66.7	2.45	4.97	88.70	9.55	8.50	18.90
	Average	56.7	2.33	3.80	78.49	8.05	7.73	16.82

SH = Shore hardness; UVW = Unit volume weight; AP = Apparent porosity; UCS = Uniaxial compression strength; TS = Tensile strength; PL = Point load strength; LAA = Los Angeles abrasion.

Table A3
Bulk density, water absorption, uniaxial compressive strength and MDA rate of andesites [47].

Sample ID	Origin of the sample(Locality)	Bulk density	Water absorption	Uniaxial compressive strength	Micro-Deval coefficient
		ρ_d	W_a	UCS	MDE
		Kg/m^3	m%	MPa	m%
G01	Gyöngyössolymos	2621	039	99.56	12.20
G02		2690	0.81	101.34	18.88
G05		2650	0.66	81.72	13.64
G06		2684	0.85	141.40	18.83
G08		2717	0.66	114.84	15.06
G09		2688	0.84	101.28	17.58
G12		2729	0.50	115.61	9.93
G13		2708	0.53	108.95	6.05
G04		2715	0.55	140.03	7.39
G11		2722	0.62	102.38	7.35
GT01	Gyöngyöstarján	2379	3.69	101.06	16.18
GT02		2456	2.54	99.82	18.51
*K*01	Komló	2530	1.58	171.87	20.94
K02		2541	1.62	67.36	24.48
K03		2540	1.35	172.38	17.11
K04		2540	1.40	176.26	21.49
K05		2539	1.37	168.88	12.31
K06		2567	1.13	174.79	11.82
K07		2583	0.88	149.51	12.61
K08		2571	1.14	133.42	12.94
K09		2591	0.83	169.32	10.08
N-01	Nógrádkövesd	2707	0.98	108.09	20.18
N-02		2717	0.89	137.29	20.92
N-03		2716	0.92	61.21	20.04
N-04		2707	0.96	81.81	18.92
N-05		2715	0.84	89.28	19.82
N-06		2705	0.93	80.24	21.33
N-07		2710	0.96	79.57	21.46
N-08		2705	0.92	83.96	19.01
N-09		2714	0.85	76.67	19.73
N-10		2712	0.81	94.41	17.71
N-11		2707	0.93	98.25	17.82
N-13		2710	0.86	52.23	19.77
R01	Recsk	2734	0.33	282.63	3.88
R02		2744	0.40	348.12	4.71
R03		2709	0.39	297.85	3.94
R04		2730	0.42	203.83	4.07
R05		2734	0.36	283.32	3.76
R06		2746	0.25	263.54	3.30
R07		2701	0.45	269.69	3.85
R08		2725	0.50	259.49	3.62
R10		2710	0.47	262.11	3.71
R11		2704	0.68	263.58	4.80
R12		2719	0.37	277.86	3.90
R13		2656	0.71	255.62	5.12
R14		2698	0.53	282.89	4.59
S01	Sárospatak	2410	2.51	43.41	25.60
S03		2446	2.51	45.42	25.60
S09		2375	2.52	60.01	25.60
S11		2498	2.41	61.85	25.60
S02		2592	1.52	117.74	14.89
S04		2605	1.24	115.03	14.89
S05		2616	1.32	111.42	14.89
S06		2599	1.48	123.99	14.89
S07		2421	3.44	79.53	19.39
S08		2469	2.80	103.55	19.39
S10		2361	2.53	73.00	19.95

Table A4
Rock mechanical parameters and estimated indicator values of several parent rock types [47].

Lithotype(Country)	Reference	ρd	Wa	UCS	MDE	A	UCS/Wa
		kg/m3	m%	MPa	m%	–	MPa/m%
Cömlekcikuyu andesite(Turkey)	Ozden and Topal 2009	2308	2.7	40.4	45.8	0.05	14.96
Dunite (Greece)	Rigopoulos et al. 2013	3180	0.32	138.12	18.35	0.38	431.63
Dunite (Greece)	Rigopoulos et al. 2013	3150	0.21	111.64	18.2	0.38	531.62
Dunite (Greece)	Rigopoulos et al. 2013	3050	0.72	62.64	21.2	0.32	87.00
Dunite (Greece)	Rigopoulos et al. 2013	3070	0.68	105.02	16.11	0.43	154.44
Dunite (Greece)	Rigopoulos et al. 2013	3010	0.85	88.34	17.24	0.40	103.93
Dunite (Greece)	Rigopoulos et al. 2013	2690	0.95	118.19	16.8	0.41	124.41
Dunite (Greece)	Rigopoulos et al. 2013	2640	1.02	102.81	19.07	0.36	100.79
Harzburgite (Greece)	Rigopoulos et al. 2013	2450	3.17	36.75	21.83	0.30	11.59
Harzburgite (Greece)	Rigopoulos et al. 2013	2570	2.29	54.05	18.6	0.37	23.60
Harzburgite (Greece)	Rigopoulos et al. 2013	2790	0.31	96.5	22	0.30	311.29
Ol-rich harzburgite (Greece)	Rigopoulos et al. 2013	3120	0.39	104.31	17.39	0.40	267.46
Ol-rich harzburgite(Greece)	Rigopoulos et al. 2013	3350	0.14	96.64	17.67	0.39	690.29
Ol-rich harzburgite(Greece)	Rigopoulos et al. 2013	3100	0.58	64.9	20.93	0.32	111.90
Troctolite(Greece)	Rigopoulos et al. 2013	2790	0.34	160.07	8.1	0.67	470.79
Troctolite(Greece)	Rigopoulos et al. 2013	2720	0.23	187.02	7.22	0.70	813.13
Trachyte(Greece)	Rigopoulos et al. 2013	2350	0.95	132.67	7.72	0.68	139.65
Trachyte(Greece)	Rigopoulos et al. 2013	2340	1.05	128.55	9.08	0.63	122.43
Trachybasalt(Turkey)	Tuncay et al.2016	2735	0.141	147.16	4.86	0.79	1043.69
PI-bearing Iherzolite(Greece)	Rigopoulos et al. 2013	2830	0.23	108.53	20.42	0.33	471.87
Diorite(Greece)	Rigopoulos et al. 2013	2760	0.31	118.12	7.3	0.69	381.03
Diorite(Greece)	Rigopoulos et al. 2013	2780	0.35	124.32	8.09	0.67	355.20
Dolerite(Greece)	Rigopoulos et al. 2013	2550	0.53	155.59	5.91	0.74	293.57
Dolerite(Greece)	Rigopoulos et al. 2013	2620	0.45	162.78	5.74	0.75	361.73
Dolerite(Greece)	Rigopoulos et al. 2013	2620	0.59	158.34	6.25	0.73	268.37
Dolerite(Greece)	Rigopoulos et al. 2013	2640	0.56	149.56	6.51	0.72	267.07
Dolerite(Greece)	Rigopoulos et al. 2013	2500	0.7	94.8	7.33	0.69	135.43
Dolerite(Greece)	Rigopoulos et al. 2013	2620	0.42	100.6	7.12	0.70	239.52
Limestone(Turkey)	Tuncay et al.2016	2590	0.298	118.2	10.06	0.60	396.64
Degirmencayi imestone(Turkey)	Ertas and Topal,2008	2371	3.31	35.7	19.6	0.35	10.79
Tirtar upper level limestone(Turkey)	Ertas and Topal,2008	2590	3.54	32.8	22.2	0.30	9.27
Tirtar middle level limestone(Turkey)	Ertas and Topal,2008	2174	4.77	21.7	32.77	0.14	4.55
Tirtar lower level limestone(Turkey)	Ertas and Topal,2008	2264	5.58	14.7	57.07	0.02	2.63
Recrystallized limestone(Turkey)	Tuncay et al.2016	2570	0.215	110.99	11.1	0.57	516.23
Dolomite(Turkey)	Tuncay et al.2016	2709	0.205	135.76	7.19	0.70	662.24
Tephra-phonolite(Turkey)	Tuncay et al.2016	2338	3.943	40.83	12.96	0.51	10.36

	Sample name	SH	UVW(g/cm^3)	AP (%)	UCS (MPa)	TS (MPa)	PL (MPa)	LAA (%)
Sediamentary	Hazar pink	51.0	2.67	1.23	110.30	8.13	6.66	22.50
	Elaszig cream	36.0	2.51	5.15	58.40	4.75	2.65	41.20
	Daisy beige	67.0	2.69	1.29	126.80	10.38	6.82	21.20
	Petrileum green	66.0	2.66	1.20	82.20	7.66	4.77	23.50
	Black pearl	60.0	2.69	0.20	108.40	8.45	5.07	20.50
	Hazar beige	55.0	2.69	0.36	61.40	5065	2.67	30.30
	Cermik beige	50.0	2.65	2.08	76.90	6.58	3.01	29.60
	Yesilova beige	56.0	2.66	0.30	70.50	6.95	4.65	26.50
	Sivrhisar beige 1	62.0	2.70	0.22	80.00	7.05	5.20	25.70
	Sivrhisar beige 2	58.0	2.69	0.22	68.00	6.09	3.70	28.10
	Diyarbakir beige	45.8	2.69	0.46	75.20	6.20	3.61	24.30
	Number of data	11	11	11	11	11	11	11
	Minimum	36.0	2.51	0.20	58.40	4.75	2.61	20.50
	Maximum	67.0	2.70	5.15	126.80	10.38	6.82	41.20
	Average	55.2	2.66	1.16	83.46	7.15	4.43	26.67
	Standard deviation	9.1	0.05	1.46	22.06	1.51	1.47	5.80
Metamorphic	Usak white	47.0	2.70	0.16	69.00	5.25	3.51	25.90
	Kozagac white	40.0	2.60	0.32	42.00	4.18	2.55	36.30
	Milas lilac	46.0	2.63	0.36	55.00	4.95	3.85	26.50
	Afyon cream	46.0	2.71	0.20	64.00	6.21	3.62	25.20
	Afyon vilet	53.7	2.70	0.17	84.19	7.44	4.67	22.60
	Kutahya green	48.9	2.70	0.20	75.53	7.69	4.53	23.20
	Afyon sugar	49.5	2.70	0.16	58.13	6.33	2.38	31.30
	Kutahya violet	50.3	2.69	0.35	63.49	6.84	3.60	24.70
	Afyon white	40.4	2.69	0.25	46.26	5.69	2.53	32.20
	Afyon violet 2	43.3	2.69	0.41	46.33	5.39	2.90	31.30
	Kutahya green 2	43.6	2.69	0.35	55.15	5.23	3.25	28.20
	Number of data	11	11	11	11	11	11	11
	Minimum	40.0	2.60	0.16	42.00	4.18	2.38	22.60
	Maximum	53.7	2.71	0.41	84.19	7.69	4.67	36.30
	Average	46.2	2.68	0.27	59.92	5.93	3.40	27.95
	Standard deviation	4.2	0.03	0.09	12.99	1.08	0.77	4.31
Igneous	Andesite 1	41.0	2.10	4.97	62.50	5.05	6.10	18.90
	Andesite 2	65.0	2.42	3.10	82.50	9.55	8.30	16.10
	Andesite 3	63.0	2.39	3.59	81.30	8.86	7.54	16.70

(continued on next page)

Table A4 (*continued*)

Sample name	SH	UVW(g/cm^3)	AP (%)	UCS (MPa)	TS (MPa)	PL (MPa)	LAA (%)
Andesite 4	43.7	2.15	4.43	71.30	6.15	7.10	18.00
Andesite 5	61.4	2.40	3.53	88.70	8.82	8.40	16.50
Andesite 6	66.7	2.45	3.16	81.50	9.25	8.50	15.90
Andesite 7	62.5	2.41	3.35	82.10	9.20	7.84	16.00
Andesite 8	59.3	2.40	3.55	85.10	8.95	8.50	15.40
Andesite 9	61.2	2.37	3.60	88.40	9.10	8.40	16.20
Andesite 10	43.0	2.18	4.70	61.50	5.53	6.58	18.50
Number of data	10	10	10	10	10	10	10
Minimum	41.0	2.10	3.10	61.50	5.05	6.10	15.40
Maximum	66.7	2.45	4.97	88.70	9.55	8.50	18.90
Average	56.7	2.33	3.80	78.49	8.05	7.73	16.82

SH = Shore hardness; UVW = Unit volume weight; AP = Apparent porosity; UCS = Uniaxial compression strength; TS = Tensile strength; PL = Point load strength; LAA = Los Angeles abrasion.

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