Research on Railroad Ballast Specification and Evaluation

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ABSTRACT

Research leading to recommended procedures for ballast selection and grading are presented. The ballast selection procedure is also presented and offers a sequential screening process to eliminate undesirable materials. The procedure classifies the surviving ballasts in terms of annual gross tonnage based on 30 tonne (33 ton) axle loading and American Railway Engineering Association grading No. 4. The effect of grading variation and its effect on track performance is also presented.

From 1970 to 1978 Transport Canada Research and Development Centre, Canadian National Railway Company, and Canadian Pacific Limited cosponsored a research program at Queen's University through the Canadian Institute of Guided Ground Transport to investigate the stresses and deformations in the railway track structure and the support under dynamic and static load systems. The findings and recommendations regarding the specification for evaluating processed rock, slag, and gravel railway ballast sources are summarized in this paper. Comments are included about the new Canadian Pacific Rail ballast specification, which was partially based on the findings presented by Raymond et al. (<u>1</u>).

The selection of the top ballast (hereafter referred to as ballast) used for railway track support is of major importance in establishing and maintaining the characteristics of the track response and, consequently, the riding quality. For ballasted track, an elastic, noncemented, stable and weatherresistant ballast bed, well laid and compacted on a stable, compact subballast and subgrade, is the first condition for low maintenance expenditures.

Ballast must be capable of withstanding many forces. Extremely large cyclic loadings, vibrations of varying frequencies and intensities, repeated wetting and drying involving crystallization of rain-dissolved soluble salts, plus other factors caused deterioration of the ballast. Ballast must also be easy to handle during maintenance. These requirements are invariably conflicting and require considerable judgment in aggregate selection for railway ballast. Some of the different requirements that should be clearly understood in making proper economic selection from available aggregate sources are outlined here.

ROCK MATERIAL

Rock consists of an intergrowth of one or more minerals. These minerals are chemical compounds and have both a specific crystal structure (or arrangement of atoms) and a specific chemical composition. Note that two or more different minerals may have the same chemical composition but will have different crystal structures. The way in which the minerals of the rock are intergrown is called the texture of the rock.

Rock names are based on the minerals that constitute the rock and the texture of the rock. Thus, two rocks of identical mineral composition having different textures would have different names. Mineral identification is generally based on simple tests that involve hardness, cleavage, luster, streak color, and chemical composition. From a ballast performance viewpoint, mineral hardness, generally based on Mohs hardness scale, is of considerable importance.

Particular geological processes give rise to three rock types, igneous, sedimentary, and metamorphic. Rock specimens may be used to classify the rock type and also to provide information about the geological history of the area where it was located. This information is valuable to the ballast selection process.

Igneous Rocks

Igneous rocks are formed from a cooling magma (a very hot, molten liquid of silicates and other compounds). The rate at which the magma cools determines the texture of the igneous rock formed. The composition of the magma determines mineralogical constituents of the rocks. These two properties, texture and composition, are the basis for the classification of igneous rocks and provide a basis for their identification.

Extrusive igneous rocks are formed when the magma is poured out onto the earth's surface. Extrusive magma solidifies rapidly to form a glassy rock or an extremely fine-grained rock.

Intrusive igneous rocks are formed when the magma cools within the earth. As such it cools slowly allowing coarser grained rocks to form. In general, the closer the intrusion comes to the earth's surface, or the smaller the size of the intrusion, the more rapidly it will cool, and the finer the grain size of the minerals will be.

Sedimentary Rocks

Under normal weathering processes, all rocks slowly disintegrate to form clay, silt, sand and gravel, plus dissolved materials, which are eventually deposited. Over time, these unconsolidated deposits may become compacted and cemented together to form clastic sedimentary rocks, whereas the dissolved materials may precipitate to form chemical sedimentary rocks.

Metamorphic Rocks

Rocks formed under one set of temperature, pressure, and chemical conditions and then exposed to a different set of conditions may undergo structural and chemical changes without melting that produce rocks with different textures and new minerals. Typically, this process results in the linear orientation of minerals along well-defined planes of weakness. This process is known as metamorphism and results in metamorphic rocks.

Comments

Although not an absolute guide, the rock formation processes outlined in the preceding sections provide a useful rough-screening criteria for ballast applications. In general, fine-grained igneous rooks are preferable to either sedimentary or metamorphic rocks. Medium to coarse-grained igneous rocks and hard, well-cemented sedimentary rocks are still preferable to most metamorphic materials.

AGGREGATE SELECTION

General

The increasing cost of track and roadbed maintenance has made the selection of an appropriate aggregate for each ballast application a matter of considerable financial importance. It is clearly not costeffective to haul a first class ballast long distances to surface a little-used branch line, and it is equally inappropriate to use an inferior ballact material on a main line track subject to a high density of heavy, fast traffic. The aggregate selection procedure must permit the decision maker to identify the physical characteristics of a ballast so as to assess the differential aspects of the material with respect to other available materials with similar properties and to evaluate, in financial terms, the expected costs and benefits from the use of each ballast.

To perform well in track, the aggregate for ballast must be tough enough to resist breakdown through fracturing under impact, and must be hard enough to resist attrition through wear at the ballast particle contacts. It must be dense enough so that it will have sufficient mass to resist lateral forces and anchor the ties in place. The aggregate must be resistant to weathering so that weakening of the ballast does not occur from crystallization or acidity of impurities dissolved in rainwater or from daily or seasonal fluctuations in temperature or other weathering processes.

It must also be resistant to the chemical degradation resulting from the action of rainwater on foreign source fines. For example, trace elements such as sulphur in coal are highly likely to increase the acidity of any moisture trapped within the ballast. This acidity will cause solution weathering of the aggregate, particularly limestones.

All aggregate material may be expected to degrade to some extent with time. Because of this it is strongly recommended that aggregates be subjected to some form of petrographic examination to assess the long term effect of the degradation and production of ballast origin fines on the ability of the ballast to remain free draining and elastic. Where aggregate is composed of fine-grained minerals whose identification is difficult to ascertain in a handheld examination, petrographic thin section analysis is strongly recommended. Thin section examination as well as a conclusive determination of rock type, mineralogy, and structure, also establishes whether microfractures exist within the aggregate source and whether former microfractures have been weakly cemented with secondary minerals that might weather and soften quickly.

Origin and Aggregate

Quarried stone ballast should be obtained from competent strata of reasonable thickness. The extent of the rock deposit should be sufficient for economic ballast production. A large variety of rock types are used as ballast. In general, the fine hard mineral-grained unweathered aggregates make the best ballast. These include igneous rock types such as rhyolite, andesite, and basalt. Second best are the coarser grained igneous rocks such as granite, diorite, and gabbro, along with the hard mineral-grained well-cemented sedimentary rock and hard mineralgrained metamorphic (or transformed) rock such as quartzite. Less satisfactory but often more commonly used because of their cheaper production cost and wider availability are the sedimentary rock types such as limestone, dolomite, sandstone, and siltstone.

Rock types such as shale and slate, which result in flaky or elongated particles, should not be permitted because these shaped particles do not result in good interlocking, particularly when subjected to vibrations. Similarly, sedimentary and metamorphic rock types that contain visible quantities of secondary minerals, which weather quickly, should be rejected. A typical example would be small quantities of pyrites, which oxidize to produce a ferric compound and then sulphuric acid, which is highly corrosive to the metallic parts of the track structure.

Where cobble and pebble size gravel is to be used to produce broken stone, it is recommended that cobble size (plus 75 mm) particles should first be sorted by the use of a coarse bar mesh. The material retained is then used as the source for crushing.

Where slag material is permitted, air cooling is generally required. No molten or meltable material should be present, and slags from hematite castings are normally prohibited. Slag should also be free from splintered or glassy components. Before the use of slags, it is generally worth examining their chemistry because their properties as ballast aggregate may often be cheaply improved by the addition of silica sand before cooling.

Petrological and Geological Requirements

A visual petrological analysis, using a hand lens or low-powered (stereo) microscope, of freshly broken rock samples is of major value in the selection of a suitable quarry. In addition, examination of the sand and smaller sized particles produced during physical testing, such as the Los Angeles abrasion test, gives an indication of the angularity and permeability of future ballast breakdown. If the minerals are fine-grained and hard, supplemental examination by means of thin section analysis and possible chemical analysis may be required. In general, the petrographer, if experienced, should be given freedom to decide the extent of the testing required.

The information obtained from the petrological analysis should be documented under those of the following headings that are appropriate to the aggregate under examination:

 Rock type of particles along with percentages where more than one rock type is present.

• Mineralogy of rock types including proportions present in each rock type.

• Texture, which should include comments on grain size, shape, orientation, plus mutual relationships and matrix material between minerals.

• Structure of rock identifying bedding planes, fracture planes, cleavage planes, and foliation planes.

• Mechanical properties from a geological point of view, including Mohs' hardness of the minerals; induration or compactness, including porosity of the rock; possible strength and brittleness, including comments on possible or existing types of fracture weaknesses; and shape and roundness of particles. Estimate of specific gravity of rock.

• Chemical properties defining existing chemical weathering and potential chemical weathering. Where known, this may be related to the environmental pollution of the locale where the aggregate is to be used.

• Properties of sand and smaller sized particles resulting from induced fracture of rock including shape, probable effect on permeability, and their susceptibility to solution and precipitation weathering.

• Suggestions with explanations for any additional engineering test not included in the testing specification.

• Estimation of expected results of engineering test results with explanation in terms of petrological features.

• Recommendations along with summary of important petrological features.

Engineering Assessment of Weathering

A number of tests are available to assess the potential of aggregates to degradation or weakening due to weathering. These include

 Soundness testing where rock particles are alternatively immersed and then dried using a salt solution. The American Railway and Engineering Association (AREA) specification calls for a solution of sodium sulphate although the author has found magnesium sulphate more appropriate, and this has been adopted in the Canadian Pacific Railway specification. The test is considered by many to be only applicable to assessing the expansive pressures generated from freezing water; however, it also provides an indirect assessment of the resistance of the aggregate to crystal growth from dissolved pollutants in rainwater through the use of a standard salt solution (e.g., magnesium sulphate). For example, the soundness test is the main test used in the United Kingdom to assess the resistance of building stone to the crystallization of soluble salts contained in rainwater that penetrates within the pores of the stone (2). In this regard building stones are observed to degrade on their surfaces depending on their degree of exposure to rainwater, the extent of atmospheric pollution, and their climatic exposure (inland or coastal and frost or no frost locations). Note that the test has been found applicable in no frost zones of the United Kingdom subject to different degrees of atmospheric pollution. Clearly the importance of the soundness test will be more significant in regions where both atmospheric pollution and freeze-thaw are greatest.

If weathering occurred independently of other factors, a higher standard for aggregates would need to be specified for branch lines than for main lines where ballast breakdown from loading is clearly less. Unfortunately, these processes are not independent, and any weakening from weathering allows accelerated breakdown from the loading environment. Thus higher standards are generally specified for ballast used in main line tracks than those used in branch lines. Because of the importance of ballast stability, the 1984 Canadian Pacific specification requires a maximum breakdown of 1 percent for primary main line track [using continuous welded rail (CWR)] rising to 3 percent for minor branch lines. This is considerably more demanding than presently required by the AREA specification (i.e., 7 percent for use with both wood and concrete ties).

 Absorption testing where oven dry ballast particles are immersed in water to measure their surface absorption. The test indicates the ability of the particles to retain water that would freeze and cause degradation during daily freeze-thaw cycles. Its importance is related to the rainfall during the time of year that freeze-thaw cycles occur and the extent of such weather. It should be noted that in the United States, many of the northernmost states and the Canadian provinces have less cyclic freeze-thaw weather than many of those U.S. states regarded as climatically warm. Again, because of the importance of ballast stability, the 1984 Canadian Pacific specification requires a maximum increase in weight of dry aggregate particles after submersion in water of 0.50 percent for primary main line track rising to 1 percent for minor branch lines. Again this is considerably more demanding than the AREA specification (unlimited for use with wood ties and 1.5 percent for use with concrete ties). Absorption may also indicate the susceptibility of an aggregate to chemical attack from any detrimental pollutants in rain water.

Stability

The properties of an aggregate that affect the holding power of a ballast are measured by

• The bulk specific gravity of the rock that is related to the unit weight of the processed ballast. The unit weight is a major factor in determining both the vertical and lateral holding capacity of the track; the holding capacity increases as the track mass increases. The 1984 Canadian Pacific specification requires a minimum of 2.60 for all lines.

• The shape and texture of the particles, which, theoretically, is a production factor. But clearly if the aggregate source is pebbles and cobbles, the source particles must be large enough to result in sufficient fractured faces after crushing. The Canadian Pacific Railway specification defines a fractured face as a freshly exposed surface whose maximum length is at least one-third the length of the maximum particle dimension and whose maximum width, measured perpendicular to the maximum fracture length direction, is at least one-quarter the maximum particle dimension. A fractured particle is defined as having not less than three fractured faces whose planes intersect at greater than 45 degrees.

Similarly, aggregate that is used to produce ballast particles that are not elongated or flaky must not exhibit excessive schistocity or slate-like structure. Examination of the laboratory crushed aggregate is a helpful but not a definitive guide to what is likely to be produced.

Load Resistant Characterization

Without exception every ballast specification attempts to assess the quality of the ballast particles under loading. Ideally this quality measure should reflect both the hardness and toughness of the mineral-bonding matrix making up the ballast particles or parent rock. The typical tests that are performed on a mix of the particles by railroads worldwide include impact testing, crushing value testing, Los Angeles abrasion testing, and the like. These tests, unfortunately, measure mainly the toughness of an aggregate and are only slightly affected by the hardness of its minerals. Satisfactory correlation has been obtained from a comparison of the results of any two of the tests (3). To make comparative measure; of the toughness of different rocks it is only necessary to use one of these tests. The Los Angeles Abrasion (LAA) test is almost universally accepted in North America. Even so, as observed from the results in Table 1, this test conducted on different sized particles results in different LAA values as does the use of track-used particles instead of freshly crushed aggregate. It is therefore important to compare ballasts on a standard size of freshly crushed particles, for example, 19 to 38 mm (0.75 to 1.5 in.), irrespective of the maximum particle size of the ballast being used. For this reason the Canadian Pacific specification requires the exclusive use of ASTM C535, Grading 3 for the LAA evaluation.

A second factor that needs understanding in relation to toughness evaluation is that for rocks of similar field rating, the impact from the LAA steel ball charge will increase slightly as the hardness of the mineral grains increases, resulting in a higher LAA breakdown. However, the field breakdown from the harder mineral rock is often slower because less powdering occurs at the points of contact between particles, and the broken particles are more angular and coarser resulting in a slower rate of track fouling. Comparisons based on LAA alone that measure primarily rock toughness would, therefore, result in decisions contrary to field performance, where better performance of ballasts with equal LAA values is noted from the ballasts composed of harder mineral grains. This is particularly evident with the use of concrete ties, where the concrete is made from silica sands having minerals of Mohs' hardness of 6 or more and are thus more abrasive than wood. Hard mineral ballasts have now been generally adopted (4). Indeed, the AREA concrete tie specifi-

cation specifically excludes carbonate ballasts (limestones composed of calcite, Mohs' hardness = 3; and dolomites, Mohs' hardness = 3.5-4) because of their recorded poor performance with concrete ties. Because rocks are composed of minerals, each having different hardness values, it was necessary to develop a method of assessing the rock's overall hardness. This was achieved by the adaption of an autogeneous grinding test known as the Mill Abrasion (MA) that is commonly used in the mining industry to access the grindability of ores (5). Rocks having a predominance of hard minerals were noted to have low MA values. Rocks having similar minerals were also noted to have a variation in values based on their degree of induration or compactness, which added to the significance of the test in terms of assessing rock hardness.

Such observations mean that a proposed ballast performance load environment class system, for financial costing purposes, was assessed from a combination of the LAA value and the MA value. Laboratory load classification research resulted in an aggregate index (I_a) renamed in the Canadian Pacific specification an abrasion number (N_a) given by

$$I_a = N_a = LAA + 5 MA \tag{1}$$

Research by Canadian Pacific has related this value to the observed life of ballast from the loading environment alone. Ballasts that weathered or were badly fouled from foreign sources were elimi nated from the study. For AREA No. 4 graded ballast, the cumulated short tons of 30 tonne (33 ton) axles to result in breakdown to the point where the ballast needed renewal was found to be given by

Life =
$$10^6 \exp(8.08 - 0.0382 N_a)$$
 short tons (2)

Test data from this author's work on different aggregates are shown in Figure 1 with a petrological description given in Table 2 that allows an estimate of aggregate life for those organizations not having an MA apparatus. It must be clearly understood that

TEST	METHOD	RESULT	AGGREGATE				
C535 C131 C131 C131 C131 C131	GRADING 3 GRADING A GRADING B GRADING C GRADING D	13.9 17.2 16.6 19.6 24.6	Andersite freshly crushed Andersite freshly crushed Andersite freshly crushed Andersite freshly crushed Andersite freshly crushed				
C5 35 C5 35	GRADING 3 GRADING 3	34–39* 25	Granite freshly crushed Granite particles already used in LAA test to obtain above result				
* Kan	ge of three te	sts on same	source.				

TABLE 1 Los Angeles Abrasion Result Finding



TABLE 2 Hand Specimen-Petrological Examination

Material	Description
Kenora granite	Granodioritic gneiss-mostly plagioclase feldspar, quartz horneblende. Hard but weak to medium toughness. Prone to fracture on foli-
Sudbury slag	Two-phase material from smelting of nickel ore-mostly silicates; very hard and relatively tough. Fine material is about 90 percent
Noranda slag	Very hard, tough material-a by-product from the smelting of copper-zinc sulphide ores. Fine material is predominantly angular frag- mentric-schould remain highly permeable
Medicine Hat Suicide Creek	Gravel containing quartite, diabase, and granite predominant; tough, medium hard, isotropic material; should retain permeability. Creek gravel, mostly granodirite with some gabbro, granite; of medium hardness and toughness; fractures on grain boundaries; ma- terial should be permeable, but could produce clave from weathering of feldsnars.
CEM-1	Initially classified as fine- to medium-grained igneous rock then identified by thin section as metamorphosed quartz diorite porphyry. Two sets of joints present with substantial weathering and secondary mineral formation on the joint planes. Fractures along joints would produce 25 to 75 mm (1 to 3 in.) blocky fragments. Mineral matrix appears sound. If main body of rock is sound and un- weathered agreeate should make excellent balast
Marmora trap rock	Actually epidote should have be one to an arrive considerably. Otherwise quite tough. Mostly calcium-magnesium-iron silicate. Chemical weathering of fines could reduce clay minerals. Otherwise should remain nermeable
CP-2	An isotropic, equi-granular grey granite, composed of plagioclas foldspar, potassium feldspar, biotite, horneblende, and quartz. Ma- tariai is touch and hard and should remain bighty permeable.
Steel (OH) slag	About 20 percent of the slag is a massive grey stone material which, although the surface is sometimes coated with a relatively soft scale, is relatively hard, tough, of high density, angular shape, and exhibits no obvious planes of weakness. The other approximately
	80 percent consists of pieces exhibiting either one or more of the following features: (a) widespread vesicles, (b) substantial fine- grained crystal growth, (c) inclusions of several materials including a soft carbonacious substance of about the consistency of coke, (d) spherical particles about 0.50 mm in diameter resting within the larger vesicles, and (e) a substantial degree of rust. Although much of the material grains are hard, the aggregate is weak, crumbling on impact and unsuitable on its own for ballast. About 5 percent of the OH material is either brick or other nondescript material presumably some flux derivative. These materials will not make good ballast.
Brandon gravel Steel (BOF) slag	River gravel; mostly gneiss of varying types; weak, medium hard, will fracture along gneissosity; permeability will be low. About 60 percent of the slag is a massive grey stone material which, although the surface is sometimes coated with a relatively soft scale, is relatively hard, tough, of high density, angular shape, and exhibits no obvious planes of weakness. The other approximately 40 percent consists of pieces exhibiting either one or more of the following features: (a) widespread vesicles, (b) substantial fine- grained crystal growth, (c) inclusions of several materials including a soft carbonacious substance of about the consistency of coke, (d) spherical particles about 0.50 mm in diameter resting within the larger vesicles, and (e) a substantial degree of rust. Although for much of this 40 percent-portion the material grains are hard, the aggregate is weak, crumbling on impact and unsuitable on its own for quality ballast. About 2 percent of the BOF material is either brick or other nondescript material, presumably some flux derivative. These materials will not make good ballast, but because of their relatively minor occurrence should have little impact on ballows of the set of the set of the set of the set of the relatively minor occurrence should have little impact on ballows of the set
Kinmberly Float	Metasediments with highly variable mineral assemblages; of medium hardness and toughness, but showing pronounced planar fabrics due to metamorphism. Should be permeable and relatively resistant to chemical weathering.
CP-1	Creek gravel; 60 percent horneblende-biotite skarn, 30 percent feldspar horneblende intrusive, and 10 percent limestone; materials
Walachin Pit	Gravel; about 65 percent skarn, 25 percent marble, 10 percent hornfels. Materials are soft, weak-marble especially prone to frac- turing on alexy are should be a percent marble.
Alberta North	Limestone, abundant crinoidal fossils; weak and soft; should remain permeable but will be prone to solutional weathering by weakly avide weakers.
PAR-1	Fine to medium-grained rather massive limestone or dolomite. Rather dirty with substantial portion of clay-sized particles among
Coteau dolomite	Thes, May be expected to abrade easily although aggregate appears tough. Tough, very fine-grained dolomite; relatively soft, but no preferred directions of fracture. Fines 95 percent powder, should remain
Saint Isidore limestone Joliette limestone	relatively permeable. Very dirty, fossiliferous limestone; soft, weak; will evolve considerable clay and sand on breakdown, which will foul ballast. Limestone, fossiliferous; soft, weak; fractures on bedding planes and cleavage of CaCO ₃ crystals. Fine material about 95 percent
Montreal limestone	Coarse-grained, clayey limestone; soft, weak; cleavage in coarse crystals forms planes or weakness encouraging fracturing. Fines about 90 percent nowed, initially permeable, but could foul with clays as weathering proceede
Megantic limestone	Compact, isotropic limestone, soft and weak; should remain permeable, but will be prone to solution weathering by weakly acidic water
Grenville marble	Non-ballast used for laboratory test comparisons. Coarsely crystalline calcite. Soft mineraled and weak. Not suitable as a ballast ma- terial
Saint Marc limestone	Coarsely crystalline, fossiliferous limestone; soft, weak; fractures on cleavage planes. Clayey material, some quartz present in fines. Permeability likely to decrease over time in track.

foreign source fouling of ballast dramatically reduces the life times given in Figure 1. For example, excessive fouling from highly plastic clay fines may result in as much as an approximate drop in the observed life.

A similar correlation or aggregate index was noted by Raymond and Diyaljee ($\underline{6}$) when load ranking ballast for permanent settlement. This suggests that the same aggregate index may be used to estimate the settlement performance between tamping cycles, provided there is no fouling from foreign source fines. For example, note the data obtained by Hay et al. ($\underline{7}$) related to ballast type and maintenance cycle shown in Figure 2. It may be observed that the finegrained hard mineral ballasts clearly outperform the soft mineral-grained and large harder grained aggregates.



FIGURE 2 North American ballast usage showing track class and resurfacing MGT (7, Table 5.1).

Apart from having limits of the LAA, MA, and N_a , the Canadian Pacific specification suggests a minimum life for ballast of 30 years and requires a life of more than 20 years based on expected line tonnage.

PRODUCTION TESTING

General

After the aggregate source for the ballast has been selected and a contract has been signed for ballast production, it is necessary to monitor its production. Although it is advisable to check the quality of the aggregate from time to time by performing the same tests as used for the aggregate selection, more important is the performance of tests to monitor the ballast properties that are production variable.

Shape and Surface of Particles

As already commented on in relation to (track) stability in the section on Aggregate Selection, the particle shape and its surface is of utmost importance and has long been recognized as having a major effect on track stability. High quality ballasts are normally required to have a high percentage of fractured faces and are required to be cubical. European practice, as given by the International Union of Railways $(\underline{\theta})$, is primarily based on limiting the percentage of particles whose ratio of longest dimension to least dimension (the least dimension is measured by passage through an infinite slot) exceeds 3, with no single particle having a ratio greater than 10. The percentage limit varies from railroad to railroad ranging from 5 to 20 percent for tolerance A ballast and 20 to 33 percent for tolerance B ballast. The desire for cuboid shaped particles is unquestionable. Canadian Pacific Rail, based on their experience with their ballast, have chosen in their specification to have no direct restrictions on particle shape but they do have stringent controls on ballast particle surface.

The Queen's University study (1) pointed out the importance of clarity regarding the definition of a crushed face. This led Canadian Pacific to conduct an extensive study of the maintenance costs associated with poorly crushed gravel ballast compared with well crushed gravel ballast. The results of these studies are reflected in the Canadian Pacific specification, which requires not less than 60 percent crushed particles for branch lines rising to not less than 90 percent for main line track built with continuous welded rail. In addition, the largest particle grading (No. 5) is required to have 100 percent crushed particles. The Canadian Pacific definition of a crushed particle is also very stringent; it requires three crushed faces whose planes must intersect at greater than 45 degrees for a parcicie to be termed a crushed particle. A crushed face is defined as being a fresh crushed surface having a maximum length not less than one-third the maximum particle dimension and whose maximum width, measured perpendicular to the maximum fracture length direction, is at least one-fourth the maximum particle dimension. Even on quarried rock these requirements will limit elongated and flaky particles.

Purity

In the case of quarried material it is always possible for clay seams or seams of soft rock to be present within the deposit. Similarly, clay or soft particles may be present in gravel sources. During production of ballast it is necessary to periodically check for purity. Three tests are normally required although they do not form part of the Canadian Pacific specification because they would be noted in the petrographic examination. These tests are used in the AREA specifications whose limits are (a) soft and friable pieces < 5 percent (< 3 percent for concrete ties), (b) material finer than No. 200 sieve < 1 percent (< 0.5 percent (< 0.5 percent for concrete ties), and (c) clay lumps < 0.5 percent (< 0.5 percent for concrete ties).

Gradation

The particle gradation of a ballast selected for track use is clearly independent of the aggregate source. Ballast gradings are usually close to uniformly graded with field productions based on the use of two or three sieves. For example, the AREA No. 4 grading, which is one of the most often used gradings, permits as an extreme 100 percent passing the 38-mm (1.50-in.) sieve with 80 percent retained on the 25-mm (1-in.) sieve. The AREA and new Canadian Pacific gradings are given in Table 3.

Single-sized ballasts have larger void volumes than broadly graded ballasts, and thus where ballast fouling from aggregate breakdown is the major source of contamination, they are generally to be preferred. Broader graded ballasts are generally

TABLE 3 AREA and CP Recommended Ballast Gradatio	TABLE	3 AREA and	CP Recommended	Ballast Gradation
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		Limits of Percent Passing Each Sieve (Square Openings) Percent by Weight								
Grading	Nominal Size									
		3"	2-1/2"	2"	1-1/2"	1"	3/4"	1/2"	3/8"	#4
AREA 24	2-1/2"~3/4"	100	90-100		25-60		0-10			
AREA 3	2" -1"		100	95- 100	30-70	0-15	_			
CP 5	2" -1"		100	90-100	35-70	0-5				0-3
AREA 4	1-1/2"-3/4"	_		100	90-100	20-55	0-15			
CP 4	1-1/2"-3/4"			100	90-100	20-55	0-5			0-3
CP 3	1-1/2"-1/2"			100	90-100	70-90	30-50	0-20		0-3
CP 2	1-1/2"-3/8"			100	90-100	70 -9 0	50-70	25-45	10-25	0-3
AREA 5	1" -3/8"				100	90-100	40-75	15-35	0-15	
AREA 57	1" -3/16"				100	95-100		25-60		0-10

stronger, and where track stability is a major concern, such as on high curvature track or track with high grades, the broader graded AREA 24 ballast or an even more broadly graded ballast may be beneficial, provided the aggregate quality is high and aggregate degradation is estimated to be minimum. Such a grading has been used by British Columbia Rail on mountain territory that has up to 12-degree curves combined with 2.2 percent grades. The aggregate source was a basalt. Before the adoption of a broad grading, an AREA No. 4 grading was in use and the maintenance cycle in this territory was as low as 3 months on the worst curves. After adoption of the grading shown in Figure 3 the lowest maintenance cycle rose to 2 years.



FIGURE 3 British Columbia Rail grading curve used to extend maintenance life cycle on high degree curves and steep grades.

TESTING

A distinction has been made between aggregate selection and its production into ballast. This distinction is recognized in the Canadian Pacific specification although no distinction has been made in relation to the frequency of testing during production. The Canadian Pacific specification requires tests to be performed every 1,000 tons compared with the AREA recommendation of every 200 tons. If the 200-ton requirement is followed it is suggested that only production-related testing as outlined here be conducted every 200 tons, whereas aggregate selection tests should be performed every 1,000 tons. Based on the author's knowledge of railroad practice, many would consider a 1,000-ton test requirement excessive.

CONCLUDING COMMENTS

The evaluation of ballast requires a two-stage process involving first an aggregate selection and then a monitoring of the processed material. The reasoning for the specification of each test and the explanation of what it evaluates is given. Generally not understood is the value that can be obtained from petrological analysis because no mention is made of its use in the ballast specification of the present AREA Manual for Railway Engineering (9). This was a major recommendation of the Queen's University research and has been made a major requirement of the new Canadian Pacific Rail specification that states (Item 4c) (10)

Where a discrepancy arises between the estimated results from the petrographic analysis and the results from other ballast material tests, the petrographic analysis shall have precedence; provided the results from the petrologist reviews all test results and identifies the reasons for the discrepancy.

Because ballast is generally made from rock and petrology is the study of rocks such a requirement is nothing more than common sense.

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