Production and Testing of Ballast

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The traditional method of selecting ballast has been based on physical testing of representative specimens to ensure that materials have adequate wearing resistance, toughness, physical stability, and strength to meet predetermined criteria. Sufficient testing is normally done to ensure that the ballast supply meets these criteria. Most tests are meant to establish that the ballast is durable at the time it is tested. Tests such as magnesium sulphate soundness or abrasion resistance give indirect evidence of how the ballast properties can be expected to change in the track structure. None of the tests currently employed, with the exception of gradation, gives direct information to explain the physical behavior and chemical stability of a ballast source, nor do they give any guidance that the engineer can use in selecting the most economical gradation or processing method for that source. The main objective of this paper is to demonstrate a rational methodology for the selection of natural rock ballast sources. To obtain the most cost-effective investment in ballast, source selection, site investigation, quarry design, quality control, and selection of specifications should be based on the geologic characteristics of the source.

Ballast is produced from rock, a natural material that was deposited and subsequently modified in accordance with natural laws of physics and chemistry. Traditionally, little attention has been paid to the character of the rock mass when selecting a ballast source. Instead, the behavior of the rock mass has been inferred from a series of physical tests. These tests are not direct measurements of the physical and chemical properties of the rock but empirical measurements that allow interpretation of ballast behavior on the basis of experience with similar materials in similar environments.

Many of the fundamental properties of the rock mass are governed by the origin, alteration, and present condition of the rock. These characteristics, cumulatively known as petrography, give insight into the mechanical properties and allow judgments to be made on how a particular source of ballast can best be exploited. This includes planning quarry operations, designing crushing circuits, and selecting gradations and specifications. All of the properties of ballast are controlled by its geologic origins and the physical environment in which it is placed. Thus a knowledge of geology is essential in locating a ballast source, designing production facilities, setting specifications, and interpreting results of quality control tests.

DESIRABLE BALLAST PROPERTIES

A summary of desirable ballast properties and related tests was given by Raymond et al. (*1*). A comprehensive investigation of ballast performance in track structures was undertaken by Canadian Pacific (CP) Rail (see paper by Klassen et al. in this Record) to determine the modes of ballast failure and the factors that affect its performance. This study resulted in adoption of new ballast standards (see Appendix, pp. 59-63 in this Record) based on observed ballast perfomance modified by a combination of physical tests and petrography.

Observations of ballast performance in track confirm the importance of those factors described by Chrismer (*2*), Selig (*3*), and others. However, the CP Rail study was unique in that it considered petrographic factors to a greater degree than had other work to date. The study results are reported elsewhere in this Record (see papers by Klassen et al. and Watters et al.). The study confirmed, by observations of ballast in the track structure, that a desirable ballast must be

1. Hard, to withstand abrasion;
2. Tough, to withstand particle fracture on impact;
3. An intact mass without pores or intercrystalline defects, to withstand the effects of freezing and thawing;
4. Chemically stable;
5. Physically stable, to resist solution, fracture, and other forms of particle breakdown;
6. Dense and rough, to give adequate stability;
7. Comprised of constant, approximately equidimensional particles with few flat or pointed particles;
8. Resistant to surface polishing that would reduce stability;
9. Permeable, able to drain rapidly;
10. Properly graded, open enough to pass fines and water but sufficiently uniform to ensure density and ease of handling;
11. Consistent, having the same qualities throughout the ballast mass;
12. Nonreactive and with low electrical conductivity, to avoid damage to rail, ties, and buried electrical systems; and
13. Resistant to abrasion but, on breaking down, preferably produces fines that are noncementing.

Klassen et al. (see paper in this Record) reported on a large number of observation trenches excavated through ballast, subballast, and subgrade in a wide range of soil types and water contents. No verifiable cases of subgrade intrusion into the subballast or subballast intrusion into the ballast were observed. The most commonly observed mode of failure was

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particle abrasion and fracture that plugged the voids with cementitious fines that caused the ballast to degrade into a cemented mass. Thus qualities related to wear resistance, fracture resistance, and the nature of fines were judged to be the most important for ensuring long ballast life.

EVALUATION BY PHYSICAL TESTING

A summary of the physical tests used by CP Rail to assess ballast quality is given in Table 1. Specifications for standard ballast gradations are given in Table 2. Most of the test methods are standard tests specified by the American Railway Engineering Association (AREA) (*4*). Unique specifications have been developed for determination of fractured particles and abrasion number and the conduct of the mill abrasion test and petrographic analysis.

A rigorous fractured-particle specification was developed to ensure adequate stability, particularly in ballast from gravel sources, and to eliminate consideration of elongated or flaky particles as acceptable fractured particles. Sampling for the fractured-particle determination is done in accordance with ASTM D 75 and C 702. From each coarse fraction representing 5 percent or more of the sample, a representative portion is selected according to the criteria given in Table 3. The samples are separated into fractured and nonfractured particles. A fractured particle is one with three or more fractured faces. Each of the faces must have a freshly exposed rock surface the largest dimension of which is at least one-third of the maximum particle dimension and the smallest dimension of which is at least one-quarter of the maximum particle dimension. The included angle formed by the intersection of the average planes of adjoining fractured faces must be less than 135 degrees for each of the faces to be considered a separate fractured face. These criteria require a fractured face to have a minimum surface area and a minimum intersection angle between fractured faces. This requirement, along with the requirement to have three fractured faces, eliminates consideration of the flaky, shard-like particles (that are common in hard, fine-grained rock) as suitable fractured particles. The weight of fractured particles is calculated as a percentage of the total sample weight.

TABLE 1 SUMMARY OF TEST METHODS AND STANDARDS FOR CP RAIL MAIN-LINE BALLAST

Parameter	Test	Test Method	Comments
Permeability	Gradation	ASTM C 136, C 117	See gradation limits
Stability	Bulk specific gravity	ASTM C 127	Greater than 2.60
Weathering	$MgSO_4$ soundness	ASTM C 88, five cycle on Ballast Grading 3	Max 1% for primary CWR[a], 1.5% for main-line jointed rail, and 3% elsewhere
	Absorption	ASTM C 127 on Ballast Grading 3	Max 0.5% for primary CWR, 0.75% for main-line jointed rail, and 1% elsewhere
Abrasion and wear	Los Angeles abrasion	ASTM 535, Grading 3	Less than 45% loss
	Mill abrasion	CP Rail	Less than 9% loss
	Abrasion number	CP Rail	Less than 65 and less than that required for cumulative tons of rail traffic for a 20-year period (from Figure 1)
Overall suitability	Petrographic analysis	CP Rail	Professional judgment to identify potential flaws

[a] CWR = continuously welded rail.
Source: CP Rail, 1983.

TABLE 2 GRADATION STANDARDS, CP RAIL BALLAST

Ballast Grading	Percentage (by weight) Finer Than 2 1/2 in.	2 in.	1 1/2 in.	1 in.	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 200
1	100	100	100	90-100	70-90	40-60	20-40	0-3	0-2
2	100	100	90-100	70-90	50-70	25-45	10-25	0-3	0-2
3	100	100	90-100	70-90	30-50	0-20	0-5	0-3	0-2
4	100	100	90-100	20-55	0-5			0-3	0-2
5	100	90-100	35-70	0-5				0-3	0-2

Source: CP Rail, 1983.

TABLE 3 SAMPLE COMPOSITION, FRACTURED-FACE TEST

Passing Sieve	Retained on Sieve	Weight (lb. ± 10%)
2 in.	1 1/2 in.	13
1 1/2 in.	1 in.	6.5
1 in.	3/4 in.	3.5
3/4 in.	1/2 in.	2.25
1/2 in.	3/8 in.	1.0
3/8 in.	No. 4	0.75

The mill abrasion test, described by Raymond et al. (*1*), uses a 6.6-lb (3-kg) sample representative of the coarse fraction of the aggregate. Three and one-third pounds (1.5 kg) of the sample are from the fraction passing the 1-in. (25-mm) and retained on the 3/4-in. (19-mm) sieve, and an equal amount is from the fraction passing the 1 1/2-in. (37.5-mm) and retained on the 1-in. (25-mm) sieve. The sample is washed and oven dried in accordance with the Los Angeles abrasion (LAA) test procedure (ASTM C 535). It is then placed in a 1-gal (4.5-L), 9-in. (229-mm) outside diameter porcelain ball mill pot, along with 6.6 lb (3 kg) of distilled water. The pot is rotated at 33 rpm for a total of 10,000 revolutions (about 5 hr), then washed through a No. 200 (71-μm) sieve and oven dried to determine the percentage loss in weight. The mill abrasion (MA) number equals loss in weight divided by original weight times 100.

The abrasion number (AN) is an index number (see paper by Klassen et al. in this Record) calculated according to the following formula:

$$AN = LAA \text{ loss in } \% + 5 \times MA \text{ loss in } \%$$

or

$$AN = LAA + 5\ MA \qquad (1)$$

PETROGRAPHIC EVALUATION

A large amount of physical testing is required to determine the uniformity and consistency of a ballast source. However, such testing gives little insight into the chemical weathering potential of a ballast or whether the physical properties will slowly change with time. Consideration of petrology, and particularly petrography, will give valuable information on the character of the rocks that may make possible a more comprehensive interpretation of the physical test results. Petrography deals with the description of the characteristics of rocks, both in-hand specimens and thin sections. Watters et al. (see paper in this Record) and CP Rail (*5*) (see Appendix, pp. 59-63 in this Record) describe the information that should be provided when an experienced petrologist performs a petrographic analysis. The megascopic features are obtained from inspection of hand specimens, and microscopic features are determined from evaluation of thin sections under a petrographic microscope. A complete petrographic description includes

1. Delineation of rock types;
2. Mineralogy of the rock types including proportions of various minerals;
3. Texture including grain size, shape, orientation, mutual relationships, and matrix materials;
4. Structure, identifying bedding, fracture, and cleavage and foliation planes;
5. Estimation of mechanical properties including hardness, strength, brittleness, and fracture characteristics;
6. Chemical properties that may affect alteration and potential chemical weathering;
7. Properties of fines produced including gradation, permeability, and susceptibility to solution or cementing; and
8. Interpretation or prediction of physical test results and identification of any special tests required.

Petrographic examination is used to verify or modify the AN determined by physical testing. When the AN is selected, the life of various ballast gradations is estimated from Figure 1. Should the anticipated life of the ballast not be adequate, an alternative source must be found.

SELECTION OF BALLAST SOURCES

A logical sequence for selection of ballast sources, both in bedrock terrain and from gravel deposits, is shown in Figure 2. Watters et al. (see paper in this Record) discuss the role of

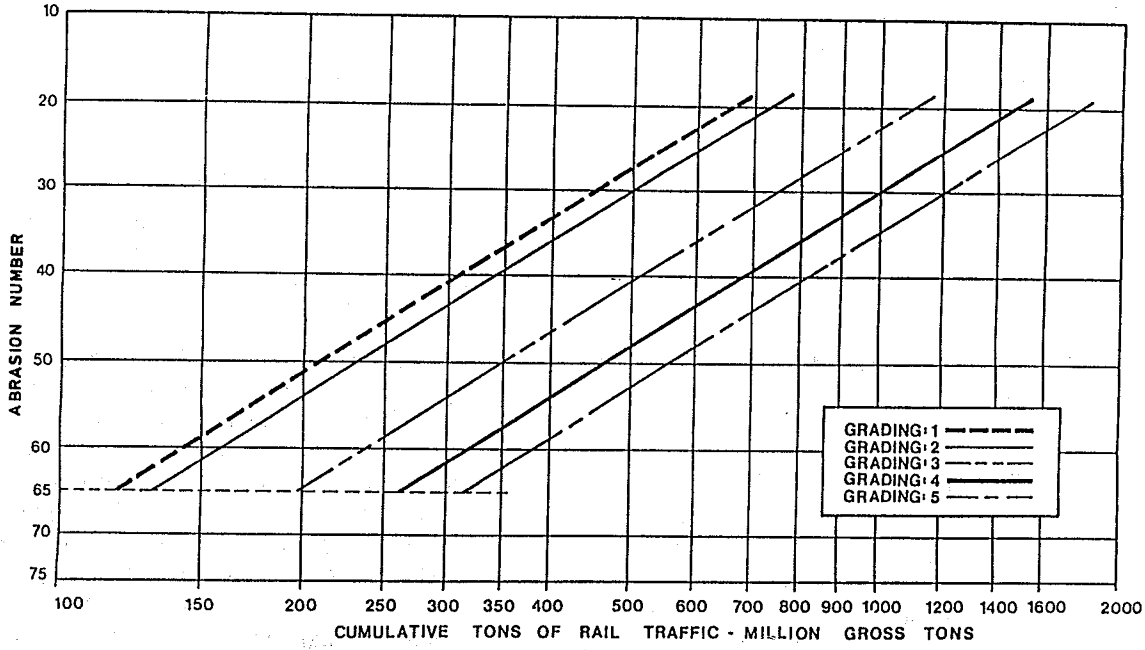

FIGURE 1 Cumulative tons of traffic versus abrasion number.

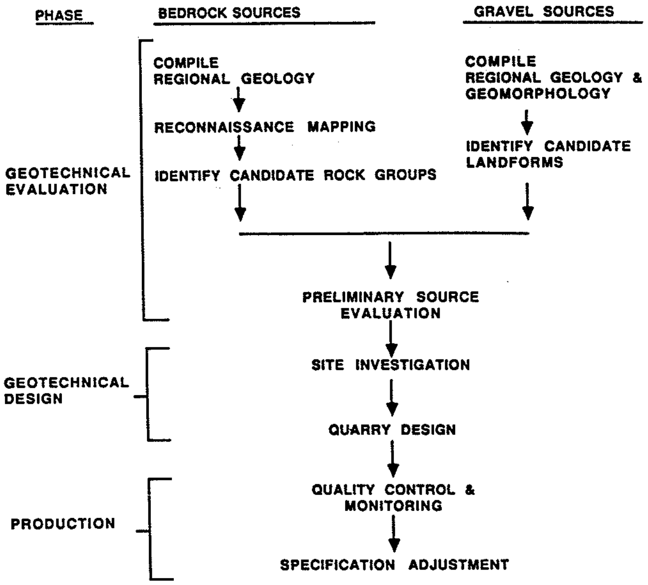

FIGURE 2 Sequence for selection of ballast sources.

geology, particularly petrography, in selecting suitable ballast sources. Candidate rock groups can be identified from consideration of geologic properties and from experience with similar materials.

The location of potential sources can be first identified through consideration of regional geology, usually available from small-scale regional geologic maps and reports. The candidate rock groups are further investigated by reconnaissance-level geologic mapping, followed by a preliminary source evaluation that includes initial petrographic screening. If the materials are deemed suitable, a detailed site investigation ensues, followed by qualification testing of the rocks recovered from cores, test trenches, and representative exposures. The geotechnical parameters and geologic structure of the rock mass must be determined so that quarry layout and crushing circuits can be designed. When production begins, quality control testing of the ballast and geologic monitoring of the source rocks is required. If necessary, the specifications may require adjustment to ensure the most economical and effective use of the quarried rock.

A similar procedure is recommended for gravel sources. The geologic evaluation consists of consideration of regional geology and geomorphology. Landforms with suitable depositional environments are identified as potential sources. These usually consist of landforms deposited in a high-energy (fluvial) environment such as terraces, point bars, and deltas on steep, fast-flowing streams and alluvial fans or eroded bedrock surfaces.

In glaciated terrain, outwash plains, eskers, kames, and eroded till plains often provide good-quality gravel sources. Geotechnical design usually includes a site investigation to determine groundwater levels, stripping ratios, and gradations of the source material. The pit design includes designation of storage areas for waste and development of reclamation plans to minimize rehandling of material during pit development. Quality control and specification adjustment procedures are similar to those employed for bedrock sources.

The implementation of this methodology is illustrated by a review of the development of a bedrock quarry near Walhachin, British Columbia, in the Thompson River Valley of Canada.

DEVELOPMENT OF THE WALHACHIN QUARRY

CP Rail required a high-quality ballast source for their main line in the lower mainland of British Columbia. This track carries in excess of 50 million gross tons per year in an area that receives high rainfall and where the ballast is subjected to freezing and thawing cycles in addition to heavy traffic. Potential quarry locations were selected after consideration of regional geology that identified a band of metamorphosed volcanics in the Thompson River Valley. However, closer examination revealed that most of these rocks had been substantially altered, which reduced their hardness. Reconnaissance identified an area of metamorphosed volcanics that consisted largely of basalt with lesser carbonate rocks. This area was in the vicinity of an abandoned quarry, which made it possible to conduct considerable geologic mapping from outcrops. Preliminary laboratory testing indicated that the unaltered basalt would produce high-quality ballast but that the softer carbonates were unacceptable. If a quarry working plan could be developed to exclude the carbonates, high-quality ballast could be produced.

Detailed mapping was undertaken to delineate the geologic structure of the area. Four test holes were cored to provide additional geologic and geotechnical information and recover representative samples of various rock types. In addition, the joint and fracture patterns in existing rocks were mapped to identify potential zones of weakness that might present a hazard during quarry operations. On the basis of these data, the geology of the site was delineated as shown in plan in Figure 3 and in a typical cross section in Figure 4. The geotechnical evaluation determined that the bench slopes should not be steeper than 65 degrees to the horizontal and that a berm width of 25 ft should be maintained. The overall slope angle on a continuous slope with no ramps should not be greater than 37 degrees. Using these parameters, the quarry plan shown in Figure 5 was developed to recover approximately 1 million tons of ballast from the quarry.

The geologic evaluation indicated that six rock types were predominant in the quarry. Petrographic evaluation indicated that the basic tuffs and breccias and basic intrusives would yield the highest quality ballast suitable for main-line continuously welded rail. The intermediate tuffs and breccias were less desirable but would produce secondary ballast with a slightly lower expected life. The calcareous tuffs and breccias, limestone breccias, and coarse intermediate breccias were judged to be unsuitable for ballast and would be used as riprap or would be wasted. The amounts of primary ballast, secondary ballast, and waste rock to be recovered from the quarry are summarized in Table 4. These data indicate that to recover approximately 1.2 million cubic yards of primary ballast and 0.2 million cubic yards of secondary ballast, approximately 1.6 million cubic yards of rock must be quarried.

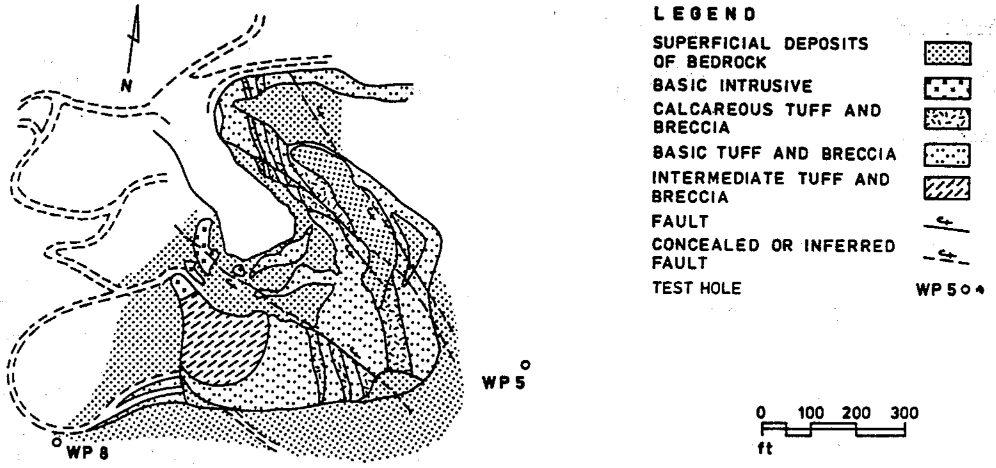

FIGURE 3 Geologic map of the Walhachin Quarry.

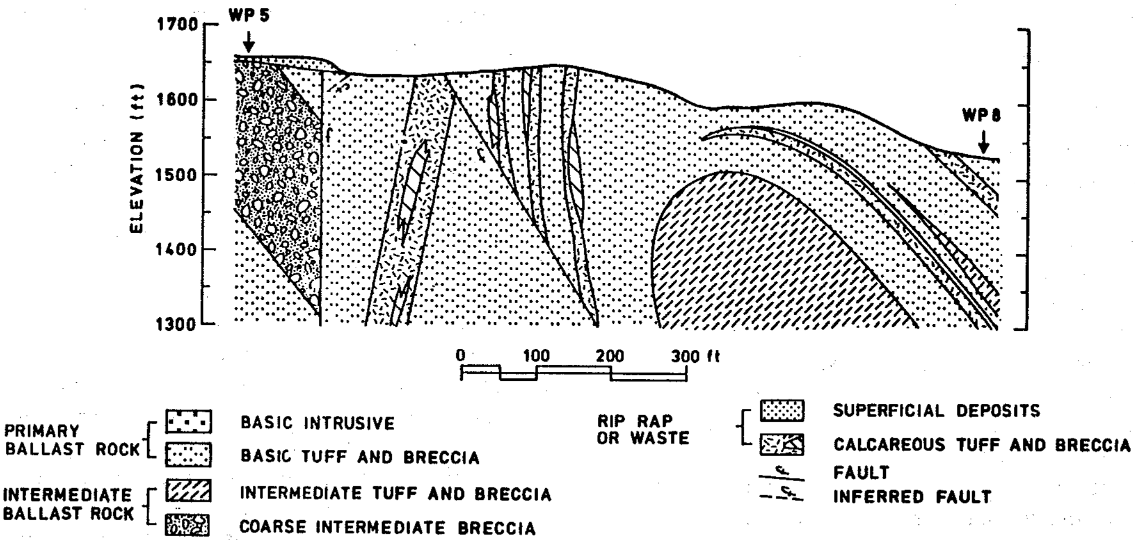

FIGURE 4 Typical cross section of the Walhachin Quarry.

TABLE 4 SUMMARY OF DESIGN QUARRY VOLUMES

Bench Level (ft above mean sea level)	Volume ($yd^3 \times 1,000$)			
	Primary Ballast	Secondary Ballast	Rock	Total
1,630	108		84	192
1,600	158		52	210
1,570	170		41	211
1,540	136		31	167
1,510	136	2	17	155
1,480	98	21	8	127
1,450	96	32	7	135
1,420	70	41	3	114
1,390	66	41		107
1,360	67	17		84
1,330	46	13		59
1,310	31	7		38
Total	1,182	174	243	1,599

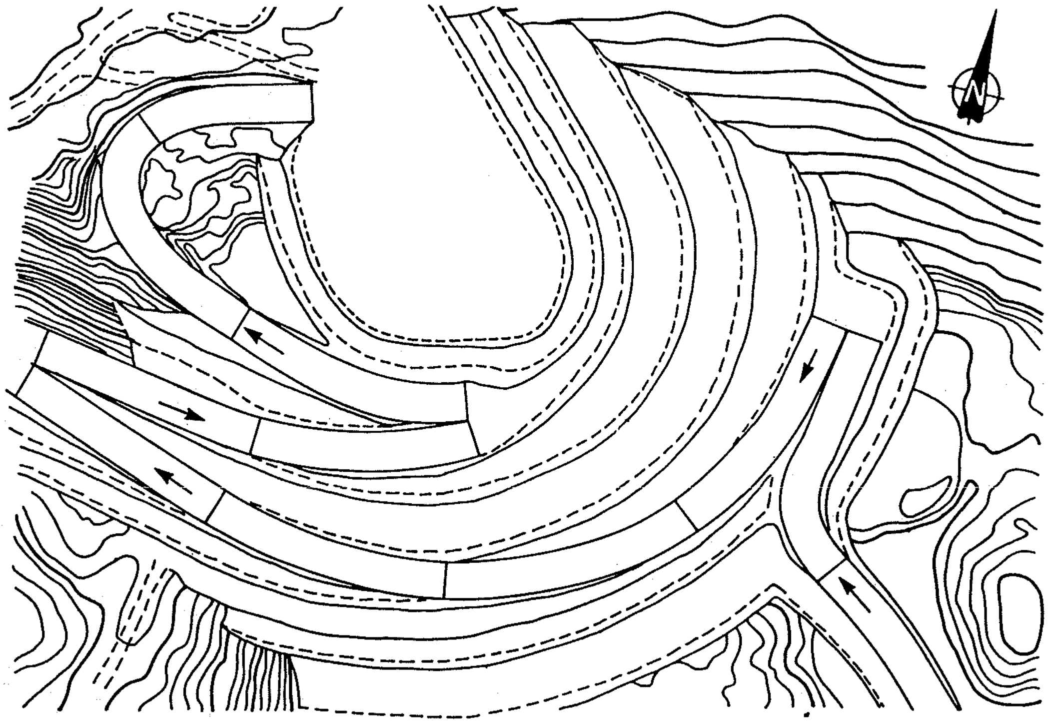

FIGURE 5 **Quarry plan.**

A contract was awarded for development of the quarry and production of CP Grading 4 (similar to AREA 4) ballast. A conventional primary jaw and secondary and finishing cone crushing circuit was envisaged, and it was estimated that approximately 40 percent of the crusher feed would be lost as reject. Quality control testing consisting of unit weight, bulk specific gravity, and gradation testing was conducted continuously on site. Other physical tests were conducted on representative samples of each rock type at various intervals. A comparison of physical test results from preliminary investigation and results obtained during production testing is given in Table 5.

The results indicate that a careful testing program conducted on materials with similar petrographic characteristics can yield reliable and reproducible results. Careful geologic control was the key to obtaining reproducible test results. Geologic control was accomplished through careful mapping of each bench and selection of material in the quarry by a qualified engineering geologist. A great deal of control was required in areas of complex geologic structures and proportionately less in areas of more homogeneous rock types.

TABLE 5 COMPARISON OF PREDEVELOPMENT AND PRODUCTION TEST RESULTS

Rock Type	LAA	MA	AN	$MgSO_4$	Absorption	Specific Gravity
Basic tuffs and breccias						
Predevelopment	11.3-17.5	1.6-3.9	19-33	1.3-3.3	.31-.68	2.77-2.96
	(14.2)[a]	(3.0)	(29)	(1.6)	(.48)	(2.82)
Production	8.8-14.8	2.2-3.9	20-34	0.6-1.5	0.2-0.8	2.79-2.86
	(12.6)	(3.1)	(28)	(0.8)	(0.6)	(2.83)
Intermediate tuffs and breccias						
Predevelopment	16.6-18.9	4.9-5.7	41-47	6.4-6.7	.48-.60	2.9-3.2
Production	13.0-16.9	2.6-5.1	26-41	0.9-2.8	0.25-1.0	2.77-2.93
	(16.7)	(4.0)	(36)	(2.1)	(.65)	(2.87)
Calcareous tuffs and breccias, limestone breccias, and coarse intermediate breccias						
Predevelopment	13.9-33.6	5.6-11.9	42-89	0.93-27	.28-.86	2.53-2.86
Production	17.9-35.7	5.8-7.7	47-74			

[a] Mean values are in parentheses.

ADJUSTMENT OF SPECIFICATIONS

Gradation changes have a significant impact on void ratio. Fuller and Thompson (*6*) proposed a method of evaluating the relationship between grain size distribution and sample porosity. Their equation is expressed as

$$P = 100\,(d/D)^n \qquad (2)$$

where

d = particle size in question,
D = maximum particle size,
P = percentage finer than, and
n = an exponent to adjust the curve.

This relationship is known as Fuller's maximum density curve and is dependent on the exponent n. The maximum density results when $n = 0.5$, but $n = 0.45$ is commonly taken as defining the practical maximum density of graded aggregate masses. This is taken as a zero air voids curve. The amount by which a ballast gradation curve deviates from the theoretical maximum density gradation is an indication of the voids in the ballast. The greater the area between the two curves, the greater the volume of voids.

The relationship between gradation and voids in a sample was determined by plotting the appropriate zero voids gradation and the ballast gradation on the same semi-logarithmic plot (Figure 6). The area bounded by the two curves, above the No. 4 sieve size, was determined by planimeter. The area was then plotted against void ratio for each sample. A linear regression analysis was used to establish the relationship between void ratio and area for various gradations (Figure 7).

The importance of voids and the necessary void ratio in a ballast are subject to some conjecture. However, examination of ballast during field studies revealed that, where ballast was poorly drained, cementing generally resulted, causing pumping of ballast fines [that fraction of the sample passing the No. 4 (4.75-mm) sieve] around the tie. Klassen et al. (see paper in this Record) concluded that a high void ratio was desirable for a high-tonnage track to prevent plugging of the voids. Studies showed that ballast with AREA 4 gradation required about 20 to 25 percent fines to plug the voids whereas a Raymond 2 gradation (*1*) required only 10 to 15 percent fines to accomplish the same degree of plugging.

The effect of gradation on void ratio was studied using Fuller's equation to predict the zero voids gradation for 2- and 2 1/2-in. top size. Ballast samples from several pits were graded to the various gradations (Raymond 1 and 2; AREA 3, 4, and 24; and CP 1 and 3) noted in Figure 7 and the void ratio was determined in the laboratory at the maximum density that could be achieved by compacting the sample with an electric "Kango" impact hammer acting on a 1-in. (25-mm) steel plate surface on top of the sample mold. This gave a density higher than that achievable by vibrating table methods (ASTM D 4253-83). The area between the gradation curve and Fuller's curve was determined for $n = 0.45$.

The relationship between void ratio and area under the curve for the various ballast samples is shown in Figure 7.

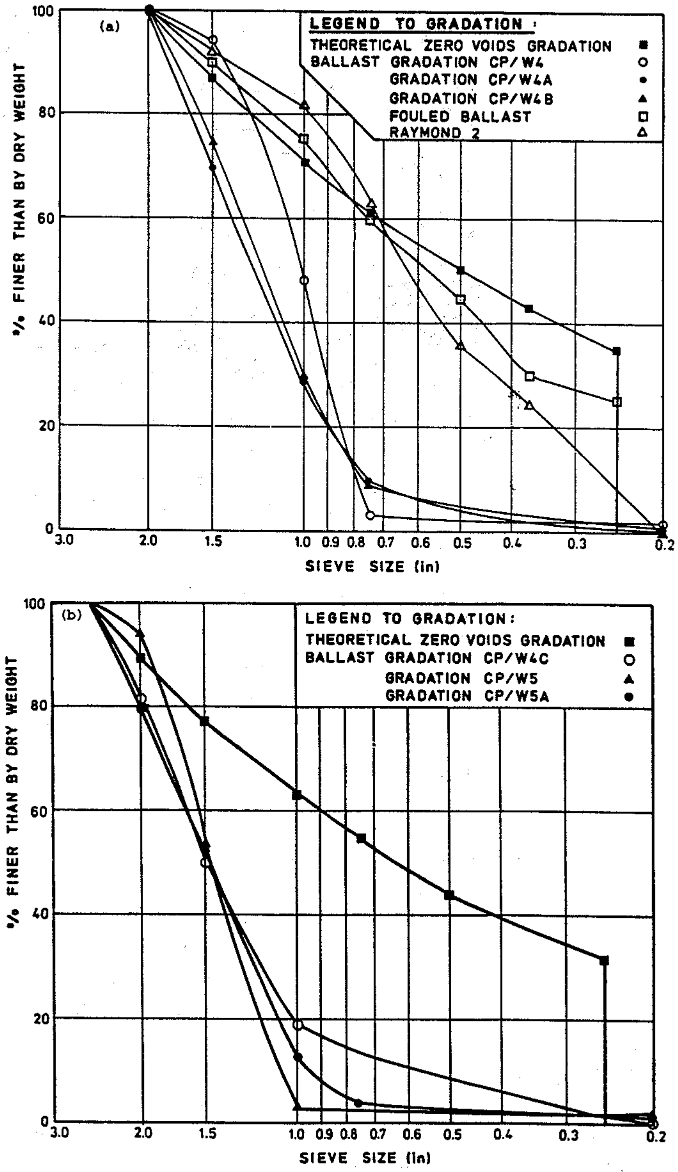

FIGURE 6 Zero voids gradation and ballast gradation.

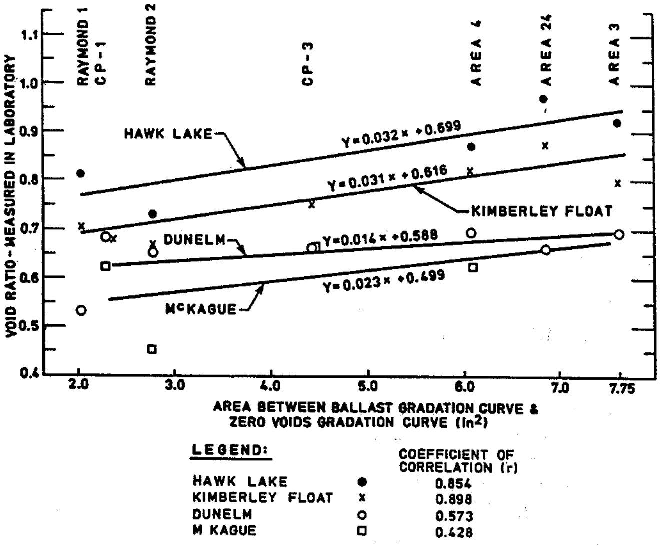

FIGURE 7 Relationship between void ratio and area.

This figure illustrates that the compaction experienced by each ballast is unique and probably dependent on particle roughness and shape. The prairie gravel samples (McKague and Dunelm) compacted more than quarried rock samples (Kimberley and Hawk Lake) and hence had fewer available voids for storage of fines. Although it is probable that ballast may compact more in track than in laboratory samples, these relationships give a subjective evaluation of the impact of gradation on void ratio and allow interpretation of the portions of the grain size curve that contribute to ballast porosity. This is further shown in Figure 6.

A number of crusher tests were undertaken to determine the ballast gradation that could be most economically produced in the Walhachin Quarry. Six trial gradations, summarized in Table 6, were produced in various tests. The amount of fines rejected and ballast produced during each test was carefully monitored using calibrated belt scales. It was found that the amount rejected was quite sensitive to ballast gradation. This sensitivity resulted from a tendency for the very hard basalt to shatter in the cone crushers when crushed to the finer gradations. Table 7 gives a summary of the yield of the quarry (tons of ballast per cubic yard of quarried rock and tons of reject per cubic yard of quarried rock) and the cost index for producing the various gradations, assuming gradation CP W4C as an index of 1.0. It can be seen that Gradation CP W5 was approximately 34 percent more expensive to produce than Gradation CP W4C for this rock type. However, it must be emphasized that these cost ratios are dependent on the rock type and processing circuits used and will vary considerably.

Figure 6a shows the theoretical maximum density gradation for 2-in. top size aggregate and the average gradation curves for the CP W4 (approximately AREA 4), CP W4A, and CP W4B gradations. Also illustrated is the typical gradation for a fouled ballast. The latter curve closely parallels the theoretical maximum density curve, indicating that few usable voids remain in the fouled ballast sample. Figure 6b shows the theoretical maximum gradation curve for 2 1/2-in. top size ballast along with average gradation curves for Walhachin trials CP W4C, CP W5, and CP W5A.

A relationship between void ratio and area under the Fuller curve can be established for any particular ballast. Figure 8 shows such a relationship for the Walhachin ballast. Also shown in Figure 8 are the void ratios corresponding to several of the trial gradations. It can be seen that changing from Gradation CP W4 to Gradation CP W4C increased the void

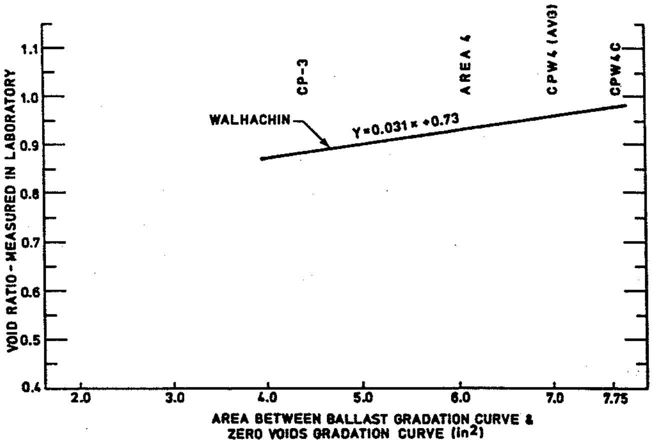

FIGURE 8 Relationship between void ratio and area for Walhachin ballast.

TABLE 6 SUMMARY OF CRUSHING TRIALS

	Percentage Passing Grading					
	CP 4	CP W4A	CP W4B	CP W4C	CP 5	CP W5A
Sieve size						
2 1/2 in.				100	100	100
2 in.	100	100	100	82	90-100	79
1 1/2 in.	90-100	69	75	50	35-70	51
1 in.	20-55	27	28	19	0-5	14
3/4 in.	0-5	10	9	6		3
No. 4	0-3	0.5	1	0.7	0-3	1
No. 200	0-2	0.1	0.5	0.2	0-2	0.6
Percentage rejected	48	40	42	39	54	45

TABLE 7 SUMMARY OF YIELD

	Grading					
	CP 4	CP W4A	CP W4B	CP W4C	CP 5	CP W5A
Ballast/yd^3 rock (tons)	1.139	1.313	1.270	1.335	1.008	1.205
Reject/yd^3 rock (tons)	1.051	0.875	0.919	0.854	1.183	0.986
Production cost index	1.12	1.01	1.04	1.0	1.34	1.08

ratio and reduced processing costs approximately 12 percent. Thus, assuming a similar void size, the ballast should have a life similar to or slightly longer than that of the original Grading CP 4 specification.

CONCLUSIONS

The geology of the ballast source is a major consideration in determining the suitability and economics of ballast production. The petrographic characteristics should be considered at an early stage in assessing the suitability of a source.

A rational approach incorporating consideration of petrography and physical test parameters has been demonstrated for the location, design, production, and monitoring of ballast production.

Specifications, arbitrarily set, can have a major impact on the cost of ballast. Experience at the Walhachin Quarry yielded at least a 34 percent differential in costs for ballast gradations with relatively minor variations.

Relatively stringent ballast gradations mean that the major impact of a specification change is in the volume of voids available to store fines. A method of evaluating the significance of gradation change that uses Fuller's equations and CP Rail's ballast performance charts has been suggested.

ACKNOWLEDGMENTS

The data presented in this paper are the result of detailed ballast studies undertaken by CP Rail and of operation of their quarry at Walhachin, British Columbia. Appreciation is expressed to CP Rail staff for making these data available.

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