Evaluation of Ballast Materials Using Petrographic Criteria

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The performance of rock ballast, when subjected to the physical stresses of loading and to the chemical and physical stresses of a weathering environment, depends to a great extent on the mineralogical, chemical, textural, and structural properties of the material. Because these properties can readily be identified by petrographic analysis, useful predictions of ballast performance can be made by the experienced petrographer. However, because of the difficulty of assessing these properties quantitatively and the large number of variable factors involved, petrographic evaluation of ballast remains, at this stage, largely a subjective process. Mineralogy is a major factor in determining overall rock hardness and physical durability, chemical weathering potential, composition and quantity of derived fines, and degree of susceptibility to wetting and drying. Rock texture also affects hardness and is important in influencing toughness, relative susceptibility to freeze-thaw degradation, and mechanical stability in track. Most of the standard tests commonly applied to ballast materials essentially provide a measure of a combination of petrographic properties; consequently, the results of the tests can be predicted to within certain limits. Numerous techniques, including the use of microscopes and X-ray diffraction equipment, can be applied in the study of the fines fraction of track samples to determine the nature and source of the material. Three ballast types in use by Canadian Pacific (CP) Rail (Kimberley Float, Walhachin, and Prairie gravels) are discussed to demonstrate the influence of petrographic properties on performance.

In general, petrography can be regarded as that branch of geology that deals with the systematic description of rock materials in hand specimens and in thin sections (a rock slice 0.3 mm thick for microscopic examination). In some instances, a petrographic study may have a broader scope and include more sophisticated techniques of examination such as X-ray diffraction (XRD) and chemical analysis. Petrographic examination is regarded by the authors as one of the most important aspects of the evaluation of ballast materials, both potential ballast and that which has seen service in the track.

The performance of rock ballast, subjected to the physical stresses of loading and the chemical and physical effects of weathering, depends to a great extent on its mineralogical, chemical, textural, and structural properties. Because these properties can readily be determined by petrographic analysis, the experienced petrographer should be capable of providing at least a qualitative assessment of the performance potential of ballast and a reasonable explanation of the failure or durability of ballast from track sections. Other properties that are significant in determining performance are particle size distribution, particle shape, and bulk specific gravity; these can be quantitatively determined and incorporated in a complete performance evaluation (see papers by Clifton et al. and Klassen et al. in this Record).

Many of the physical and chemical tests commonly applied to ballast materials (e.g., mill abrasion, Los Angeles abrasion, magnesium soundness, and absorption) essentially provide a quantitative measure of petrographic properties. Consequently, it is generally possible to predict, to within certain limits, the results of these tests. It follows, therefore, that a complete petrographic analysis should always be the first step in the evaluation of ballast materials and should constitute the basis on which further testing is carried out. Furthermore, petrography should be regarded as a key factor in the selection of a ballast source (see paper by Clifton et al. in this Record).

The relatively low cost of a petrographic analysis can generally be well justified in terms of potential savings in other tests, quite apart from the enormous cost of replacement of unsatisfactory ballast.

PETROGRAPHIC EXAMINATION PROCEDURES

During the initial stages of an extensive ballast evaluation program carried out by CP Rail (see paper by Klassen et al. in this Record) the authors developed a standard procedure for petrographic examination of samples and set up a scheme for the description and reporting of results of such analyses.

This scheme is presented in outline form in the following list (see also Appendix, pp. 59-63 of this Record), and some aspects are discussed briefly.

a. Rock types: Identification, estimation of relative proportions in various size fractions.
b. Mineralogy: Should include estimation of relative proportions of all rock types. Surface encrustations should also be noted.
c. Texture: Nature of the constituent particles or crystals of each rock type, their mutual relationships, shape and orientation, nature of matrix and consolidation, porosity.
d. Structure: Fractures, joints, foliation, mineralogical banding, bedding, or lamination.

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e. Mechanical properties
   (1) Hardness,
   (2) Toughness,
   (3) Shape and surface characteristics of particles,
   (4) Freeze-thaw and wetting and drying, and
   (5) Properties of fines and permeability.
f. Chemical properties: Existing state of weathering, potential for chemical degradation, weathering potential of derived fines.
g. Estimated results of tests: Los Angeles abrasion, mill abrasion, Mg soundness, absorption, bulk specific gravity.
h. Specific tests recommended.
i. Summary, including recommendations for use as ballast.

The scheme is based on normal petrographic analytical procedures commonly used in the geological sciences (*1-3*) that have been adapted to the requirements of ballast evaluation. For example, one essential aspect of a petrographic report is not only a statement regarding the present condition of the material but also an estimation of the manner in which it will withstand the rigors of use in track.

The equipment necessary to carry out a petrographic analysis can range from very basic to highly sophisticated depending on the specific requirements of the investigation and the nature of the rock material being dealt with. The majority of analyses can be conducted by visual examination of materials in hand specimen and with the aid of a stereoscopic microscope (up to 40× magnification).

Ideally, every petrographic analysis should include examination, under the petrographic microscope (polarizing), of thin sections of all rock types making up the sample. However, time and cost factors do not always permit this, so this type of examination is often reserved for special cases only. Thin-section examination techniques have been described by many authors (*1, 3-6*) and will not be elaborated on here. If thin sections are not available, rock crushes (-80 to +100 mesh size) can be easily prepared and, immersed in a suitable liquid medium (*7*), examined under a petrographic microscope. This is a quick and reasonably good method of identifying the major mineral components of igneous and metamorphic rocks, but it does not provide information regarding textural properties and minor minerals and is also of limited use in dealing with fine-grained rocks.

Examination of the finer fractions (minus No. 4) of a ballast sample can also be conducted to a great extent using a microscope. However, it will not always be possible to positively identify much of the finest material in these fractions by this method, and more sophisticated techniques, such as XRD analysis (*8, 9*) may have to be employed. Only rarely is chemical analysis used in routine ballast investigations, although such methods can be useful when dealing with extremely fine-grained or amorphous materials and may also have considerable potential for solving problems related to the nature and source of fines.

Although a petrographic examination can be carried out by any competent petrographer, the value of the analysis will be vastly enhanced if the petrographer has experience in relating petrographic properties to standard mechanical and chemical tests and to actual performance of ballast rock materials in track.

The identification of rock types in ballast and the determination of the relative proportions present in each size fraction form the basis of any performance evaluation. There are three major rock groups, igneous, metamorphic, and sedimentary, and all yield types suitable for ballast. Classification of rock types can be done according to standard schemes (*2, 10, 11*) which use mainly mineralogical and textural criteria. Mineralogy involves identification of mineral constituents and an estimation of their relative proportions. Texture refers to the size, shape, and mutual relations of the component crystals or particles of a rock (*1, 6*).

Determination of mineralogy and gross textural features can be achieved, in most cases, by examination of hand specimens under a stereoscopic microscope, although it is generally recommended that, whenever possible, this be supplemented by thin-section analysis. The latter will permit more accurate determination of mineralogy, texture, and, in the case of certain igneous rocks, the identification of deuteric (late-magmatic) alteration effects (*2, 11*).

In a petrographic context, structure refers to the mutual relationships among various parts of a rock, which often represent distinct textural units. At the scale of ballast particle size (usually <2.5 in.), many structures of the source rock mass will not be present and are, therefore, of no great importance with regard to ballast evaluation. However, small-scale structures (e.g., finely spaced joints and fractures) are important and there is considerable overlap in what can be regarded as a "textural property" and a "small-scale structure."

The hardness of individual minerals is independent of properties such as texture and cleavage fracture and can be quantitatively determined according to Mohs' scale of mineral hardness (*2*). However, when applied to rocks, the concept of hardness takes on a somewhat different meaning because rocks are usually assemblages of a variety of different minerals. In a strict sense, Mohs' hardness is not directly applicable to rocks, particularly the coarser-grained types. For this reason, the authors prefer the term "effective hardness," which is essentially an estimate, in terms of Mohs' scale, of the overall hardness (or a measure of resistance to abrasion) of the rock material. Such an estimate is based on the hardness characteristics of the constituent minerals, their relative proportions, potential for cleavage fracture, and textural properties. Because of the many variables that influence the effective hardness of a multimineralic material, it is not possible for the petrographer to accurately quantify hardness, especially for the coarse-grained materials. In terms of resistance to abrasion, fine-grained rocks tend to behave more like mineralogically homogeneous materials and their effective hardness characteristics can, consequently, be more accurately assessed. Mill abrasion (MA) tests essentially measure the effective hardness of the ballast.

Estimation of mineral and rock hardness relative to Mohs' scale (*6, 12*) can be achieved using a complete set of Mohs' hardness specimens. However, it is generally more practical (and adequate) to use simple implements such as a pocket

knife and copper coin (of relative hardnesses 5 to 5.5 and 3.5, respectively) to bracket the hardness of the materials under examination.

If the ballast is composed of a single rock type, these methods can provide a reasonably accurate hardness value. However, if the ballast is a mixture of materials of differing hardnesses, the relative proportions of the various rock types must be taken into account.

Toughness, a measure of resistance to impact-type stresses, can also be estimated on the basis of mineralogical, textural, and structural properties but cannot be related to a scale in the way hardness can. The Los Angeles abrasion (LAA) test essentially provides a measure of the toughness characteristics of an aggregate.

It is generally not cost-effective or otherwise appropriate for the petrographer to conduct formal tests to determine particle shape. However, the petrographer can determine, qualitatively, any unsuitable shape bias and provide reasonable explanation for such bias. In the assessment of ballast that has seen service in track, an appraisal can be made of current particle shape and the extent of modification by abrasion, impact, and weathering since installation.

The potential for degradation of ballast as a result of freeze-thaw and wetting and drying can be fairly reliably assessed. By considering the mineralogy, hardness and toughness characteristics, and relative proportions of different rock types making up a ballast sample, it is possible to estimate the mineralogical makeup of the derived fine fraction. As will be discussed in a later section, useful predictions of the rate of fouling and permeability loss are extremely difficult to make.

In the evaluation of new or potential ballast, two aspects of chemical weathering have to be taken into account: first, the extent of original weathering and, second, the potential for weathering after the material is placed in the track. The extent to which the rock may have been weathered in the source is easy to establish and constitutes part of a normal petrographic analysis. Rock chosen for ballast is generally free of any extensive chemical weathering because this is an important criterion in the selection of the source. Determining the extent of chemical weathering of ballast that has been in track is also simply a matter of routine petrographic examination. However, the degree to which the derived fines may have been weathered and altered (to clays, for example) is rather more difficult to establish.

Test results can usually be semiquantitatively predicted on the basis of petrographic criteria. However, this should not be regarded as a substitute for all quantitative testing. The petrographer can make recommendations for specific tests if there is any doubt about the suitability of material and, if the petrographic analysis indicates the material to be of unacceptable quality for ballast, further costly testing can be avoided.

INFLUENCE OF PETROGRAPHIC PROPERTIES AND ASSESSMENT OF BALLAST PERFORMANCE

To assess the performance potential of ballast materials, a large number of factors have to be taken into account. Other than petrographic characteristics, factors such as track loading, environmental conditions, and particle shape and size distribution may all be of importance. There is no simple formula that can be applied in the performance evaluation of ballast using petrographic criteria. Consequently, any such assessment is a subjective process: the relative importance assigned to any single factor, or combination of factors, is dependent on the experience of the petrographer.

In spite of these limitations, petrographic analysis is of great value because it can be used to provide a qualitative assessment of performance in the track, predict qualitatively the results of tests, provide rational explanations of test results, identify potential problems in materials intended for use as ballast, provide reasons for failure (so that the same mistakes are not repeated), and monitor material from sources and from track sections. Specifications for the selection of ballast materials (see Appendix, pp. 59-63 in this Record) are based largely on physical test criteria. Because the results of such tests will be determined to a great extent by petrographic properties, qualitative estimation of test results using petrographic data will permit evaluation of potential ballast materials. Therefore the following discussion will be concerned primarily with the influence of petrographic character on certain properties critical to the selection of ballast (e.g., hardness, toughness, and chemical weathering potential).

Hardness

Hardness is judged to be the dominant characteristic determining the physical durability of ballast. As discussed earlier, the effective hardness of a rock will depend not only on the hardness of the component minerals but also on mineral cleavage fracture, textural attributes, and, in the case of clastic sedimentary rocks, the degree of cementation or consolidation.

Crystalline rock types composed of soft minerals degrade more rapidly than do those made up dominantly of hard minerals. Furthermore, as is pointed out later, hardness also plays a part in determining the toughness of rock materials, another important criterion commonly used in the selection of ballast (see Appendix, pp. 59-63 in this Record). The hardnesses of common rock-forming minerals are given in Table 1, and it is apparent that most of the anhydrous silicate minerals (e.g., quartz, feldspar) are harder than and will constitute far superior ballast rock components than the hydrous phyllosilicates (clays, chlorite, mica) and carbonates.

The property of cleavage fracture in constituent minerals will lower the effective hardness of a rock. When subjected to abrasion (and impact) stresses, the crystals will tend to fracture along cleavage planes and the influence of this effect on hardness will be far greater for coarse crystalline rocks than for the finer-grained varieties. Friable texture, occasionally present in crystalline igneous and metamorphic rocks, will also have a significant negative influence on effective hardness.

TABLE 1 SOME PROPERTIES OF COMMON MINERALS RELEVANT TO BALLAST ROCK EVALUATION

Mineral	Mohs' Hardness	Potential for Cleavage Fracture	Chemical Weathering Potential of: Ballast Particle	Chemical Weathering Potential of: Fines	Specific Gravity	Suitability as a Ballast Rock Component (durability)
Quartz	7	Nil	Nil	Nil	2.65	High
Plagioclase feldspar	6-6.5	High	Low	High	2.60-2.74	Moderate
Potassium feldspar	6	High	Low	High	2.57	Moderate
Hornblende	5-6	Moderate	Low	Low	3.00-3.47	Moderate
Actinolite	5-6	Moderate to high	High	Very high	2.90-3.20	Low
Mica	2-3	High	Moderate	Moderate	2.76-3.10	Low (soft)
Pyroxene	5-6	Moderate	Moderate	High	3.20-3.50	Low to moderate
Chlorite	1.5-2.5	High	Low	Low	2.65-2.94	Very low (soft)
Clay minerals	1-2.5	High	Low	Low	2.60-2.90	Highly unsuitable
Epidote	6-7	Low	Very low	Very low	3.25-3.50	High
Tourmaline	7-7.5	Very low	Nil	Nil	2.98-3.20	High
Garnet	7-7.5	Nil	Nil	Nil	3.50-4.20	High
Olivine	6-7	Nil	Very high	Very high	3.20-4.30	Low
Calcite	3	Very high	High	High	2.71	Low
Dolomite	3.5-4	Very high	Moderate	High	2.80-2.90	Low
Magnetite	5.5-6.5	Very low	Very low	Very low	5.18	High
Pyrite	6-6.5	Nil	Moderately high	Very high	4.80-5.10	Unsuitable
Pyrrhotite	3.5-4.5	Low	Very high	Very high	4.40-4.65	Highly unsuitable

The effective hardness of clastic sedimentary rocks (and most volcaniclastic rocks) will be determined primarily by the nature of consolidation, which can be regarded as involving one or more of the following: compaction, cementation, and recrystallization. Compaction will not, on its own, produce a rock sufficiently hard and durable for use as ballast. Because this is the dominant factor involved in the consolidation of fine-grained rocks such as mudstones and shales, these types are unacceptable as ballast. Common cements in sedimentary rocks are silica, carbonates, and iron oxides and hydroxides. Grains well cemented by secondary silica minerals will be strongly consolidated, especially if the grains are quartz and the cement occurs as grain overgrowths. Secondary iron minerals constitute a weak to moderately strong cement depending on abundance. Carbonate cements (mainly calcite) are weak; they are limited in strength by the softness and prominent cleavage that characterize these minerals. Interstitial clay minerals can also constitute a weak cementing agent.

Recrystallization may occur in sedimentary rocks subjected to somewhat elevated temperatures that border on metamorphic conditions. Sedimentary rocks rich in quartz grains (e.g., quartz sandstone) commonly recrystallize to form a very well-indurated rock called orthoquartzite, which has a high hardness (H = 7). Carbonate rocks (limestone and dolostone) also commonly recrystallize, but effective hardness will still be low (3 to 3.5) because of the low hardness and prominent cleavage of the constituent minerals, calcite and dolomite.

The effective hardness of a ballast rock type can be estimated using the simple techniques already discussed. A weighted average hardness value (in terms of Mohs' hardness) for the ballast sample can be calculated taking the relative proportions of the constituent rock types into account. Such a value can only be expected to represent an approximation of the hardness characteristics of the ballast as reflected by abrasion in track and by mill abrasion testing because it does not take into account the effects of particle shape, particle surface characteristics, and relative hardness of constituent rock types. Consequently, the petrographer can usually only report ballast hardness in general terms such as "low" ($H < 4?$), "medium" ($H = 4$ to $5.5?$), and "high" ($H > 5.5?$), the subdivisions being somewhat arbitrary.

Relating a petrographically estimated hardness value to an equivalent in terms of mill abrasion loss can also only be achieved on a semiquantitative basis, the more so because the steps on Mohs' scale are not equal. Although there is considerable overlap in the ranges, "low," "medium," and "high" hardness ballasts will display high (> 6 percent?), moderate (about 4 to 6 percent?), and low (< 4 percent?) mill abrasion losses, respectively.

As discussed in the section on Case Histories, a more reliable correlation between petrographically estimated hardness and mill abrasion can be achieved if a considerable amount of data is available for a particular ballast type, especially if the material has variable hardness. This allows a plot of petrographic hardness versus abrasion value (MA, or abrasion number, as discussed below) to be drawn.

It has been shown (see paper by Klassen et al. in this Record) that the overall physical durability of ballast can be estimated by determining its abrasion number (AN), which is calculated according to the formula:

$$AN = \text{Los Angeles abrasion} + 5 \times \text{Mill abrasion}$$

Because the mill abrasion test is essentially a measure of the hardness of the material, and toughness will also depend on this property to some extent, this equation is further indication

of the importance of hardness in determining the durability of ballast. Abrasion number constitutes an important criterion used by CP Rail in the classification of ballast (see Appendix, pp. 59-63 in this Record).

Toughness

Major factors that influence the toughness of a rock, its ability to withstand impact-type stress, are hardness and textural and structural features that may lead to fracture. Finely spaced joints or fractures (< 2 in.) constitute an undesirable structural element, and losses due to impact will be far greater for a rock composed of very soft minerals (e.g., calcite in limestone) than for one made up of very hard minerals (e.g., quartz in quartzite). If the rock is crystalline and coarse grained, cleavage fracture in some minerals may cause relatively high losses (e.g., feldspars in granite and gneiss, and calcite and dolomite in limestone and dolostone, respectively).

Finely crystalline igneous and metamorphic rocks and well-consolidated fine-grained sedimentary rocks tend to be tough, provided they are free from obvious or incipient fractures and planes of weakness. It is frequently the case that coarsely crystalline igneous and metamorphic rocks tend to have somewhat friable textures. Similarly, coarse-grained clastic sedimentary rocks are generally less well consolidated than their finer counterparts. Furthermore, soft, well-bedded or laminated sedimentary rocks, such as shale, will be very weak.

Strongly foliated metamorphic rocks such as schist, slate, and phyllite, all of which are commonly rich in mica (a very soft mineral), are generally not very tough. Foliated rocks poor in mica, such as some amphibolites, tend not to part as easily along foliation planes because their mineral cleavage planes do not have such a consistent parallel alignment. In coarse-grained, mica-poor gneisses, the major mineral constituents of which are more or less equidimensional, foliation is defined more by a concentration of minerals into bands than by a strong preferred orientation of crystals, and the foliation does not constitute a prominent weakness.

The tenacity of a mineral refers to properties such as brittleness, elasticity, and flexibility. In extreme cases, these may influence the toughness of a rock composed dominantly of one mineral type. For example, rocks composed dominantly of quartz, such as quartzite, tend to be brittle and produce shardlike (flaky) fragments on impact.

Voids, such as intergranular spaces in a sedimentary rock (porosity) or vesicles in a volcanic rock, may, if sufficiently abundant, seriously weaken a rock and reduce toughness as a consequence. Veins cutting through a rock may also represent weak zones, depending on the vein-filling mineral. A weak mineral such as calcite is poor, whereas quartz as a vein-filling material is very strong.

Although he will not be able to provide a quantitative assessment of toughness, the petrographer will usually be able to rate a ballast as having low (= LAA > 40?), medium (= LAA 30-40?), or high (= LAA < 30?) toughness and provide an indication of any potential problems. The apparent lack of a consistent correlation between LAA test data and track performance characteristics discussed by Chrismer (*13*) suggests that this type of information, based on petrography, can be of considerable value.

Particle Shape and Surface Characteristics

For good mechanical stability in track, ballast particles should, ideally, be angular and equidimensional in shape (*14*) with rough surfaces to provide maximum friction between particles. For example, rock types such as granite and gneiss usually have rough surfaces whereas quartzite, although very hard and durable, has very smooth surfaces that offer limited friction between particles and consequent poor stability. Very hard, fine-grained rock types also tend to acquire a surface "polish" in track, which further reduces interparticle friction.

Well-rounded particles, or particles with a high proportion of rounded surfaces, such as those common in some glacial gravel ballasts, will constitute a very unstable track bed, especially if the particle surfaces are smooth.

Strongly foliated metamorphic rocks will be weak in one plane, and pronounced tabular or elongated particle shapes, or both, will result from the crushing of such material as well as from fracture in the track as a result of impact. Particles that have strongly developed elongated or flattened shapes, or both, will also be mechanically unstable and have the added disadvantage of being subject to load fracture. Therefore rock types that are rich in mica and have a strong foliation, such as many schists, phyllite, and slate, are highly unsuitable as ballast components.

Particle shape will also influence the results of abrasion tests and is an important factor in the evaluation of ballast from track sections or the comparison of test results of such material with those from fresh source samples. Angular particles will abrade more rapidly, initially, than rounded particles in both types of abrasion tests (and also in track) because the relatively "sharp" edges of the former will be highly susceptible to removal. Similarly, ballast particles that have already suffered abrasion in track and have undergone some shape modification (less angular) but have remained essentially unweathered will provide lower abrasion values (and appear of higher quality) than fresh source material of the same type. This effect is likely to be significant in the majority of cases and should always be kept in mind when making comparisons between sets of abrasion data. This principle can be well illustrated by conducting repeated abrasion tests on the same ballast samples, as was done for various rock types from the Walhachin Quarry. The test results indicate a 10 to 30 percent and a 35 to 50 percent reduction in LAA and MA results, respectively, and a more consistent 25 to 35 percent reduction in AN. This tendency is, however, not clear-cut and the effect may be converse. If the particles have developed soft weathered mantles in the track, abrasion losses may increase, compared with those for fresh material, in spite of the particles being less angular.

Freeze-Thaw and Wetting and Drying

Breakdown by freeze-thaw will depend, to a great extent, on the porosity and permeability of the rock materials and can take the form of intergranular voids and bedding plane partings in clastic sedimentary rocks, cavities in crystalline sedimentary rocks such as limestone and dolostone, vesicles in volcanic rocks, intercrystalline and cleavage partings in coarse-grained crystalline rocks, and joints and fractures. These features can readily be identified by petrographic examination, particularly if thin sections are available. Relating these properties quantitatively to some soundness index is not possible except in quite general terms (such as "low," "moderate," and "high"). Certainly, petrography can identify those materials that will produce low soundness test results (e.g., Mg soundness) and those that are likely to give unacceptably high values.

Abrasion and impact in track will produce mantles and spots of physically broken down material on ballast particles, which will be relatively porous, loosely cohesive, and subject to removal by freeze-thaw (as well as by further abrasion). In this way, fresh rock is continually being exposed. The contribution of this process to the overall degradation of the material is judged to be significant, but further research is needed to establish this point.

The absorption characteristics of a ballast will depend on petrographic properties similar to soundness and can also only be qualitatively estimated.

Wetting and drying of clay-bearing materials will result in alternate expansion and contraction of the clays causing a physical deterioration. Relatively minor quantities of clay (a few percent) in some sedimentary rocks may be deleterious if the clays are of the swelling type. This latter property can be determined by XRD analysis (*9*).

Chemical Weathering

The potential for weathering of both the ballast particles and the derived fines is determined primarily by mineralogy (Table 1) and environmental factors. Texture and structure may also play a minor role in that friable, porous, or fractured rocks provide more surface area at which weathering reactions can occur. Chemical weathering of minerals comprising the ballast rock types will usually not be the primary cause of failure of the material because, under normal environmental conditions, most common major rock-forming minerals are relatively resistant to this type of breakdown. However, even minor proportions of some minerals, such as sulfides and olivine, may be deleterious. The latter will rapidly break down to serpentine or talc (very soft), and sulfide minerals will oxidize and, in doing so, generate an acidic environment in the ballast that will, in turn, accelerate the chemical weathering of both the ballast rock and the derived fines. In general, rock types that contain excessive amounts of sulfides and olivine (greater than about 2 and 5 percent, respectively) should not be considered for ballast.

Fines derived from the physical breakdown of ballast particles will be far more susceptible to chemical weathering than the larger parent particles (Table 1) because of the much greater surface area per unit volume exposed to atmospheric elements. For example, fines derived from feldspars, common major mineral constituents of many rock types, can be expected to break down to clay minerals far more rapidly than the parent feldspar crystals.

Carbonate rocks will weather primarily by solutioning, a process that frequently produces thin, soft, powdery mantles on the particles. Such mantles are easily removed by abrasion and freeze-thaw and thereby contribute to the fines fraction and expose fresh rock for further weathering. Furthermore, if the rock is impure, dissolution of any part of the carbonate component will release insoluble particles, commonly clay. Consequently, although "clean" carbonate rocks can constitute satisfactory low-grade ballasts, impure varieties are highly unsuitable.

Another form of alteration, distinct from chemical weathering (a low-temperature process), is deuteric alteration, which takes place at high temperatures during the late-magmatic stages of the formation of an igneous rock mass. In deuteric alteration the primary minerals alter to secondary minerals that are generally softer and less desirable as ballast rock constituents. Recognition of these effects, not always obvious in hand specimen, is important especially for predicting the constitution of the fines component.

Material taken from track sections will often be weathered to some degree and particles may have mantles of relatively soft alteration products. Furthermore, after being in the track for a few years, ballast particles may acquire coatings of oil and loosely adhering grime, which add to the soft mantle. During abrasion tests this soft material will be easily removed, resulting in higher abrasion values compared with those of fresh material from the same source. Testing of Kimberley Float ballast taken from the source and of that placed in track at various times provided a graphic example of these effects, as described in the section on Case Histories.

Bulk Specific Gravity

The bulk specific gravity (BSG) of ballast materials will depend primarily on the mineralogy of the constituent rock types and their relative proportions. Another factor that is of significance is the presence of void spaces (porosity, vesicles, etc.) in any of the rock types. All of these petrographic properties can be quantitatively determined. Therefore, because the specific gravities of all minerals are known (Table 1), a simple calculation can provide a fairly accurate estimation of the BSG of the aggregate.

IDENTIFICATION OF "FATAL FLAWS"

Although it is possible to identify certain petrographic properties that are likely to render a rock material unacceptable as ballast, it should be realized that the presence of undesirable properties, if "diluted" by acceptable qualities,

can be tolerated because they may simply limit the application of the material (instead of making it totally unacceptable). For a particular petrographic property to constitute a "fatal flaw" it is generally necessary for it to be present in relative abundance. The principal petrographic properties that may cause a material to be of fatally poor quality as ballast have been summarized in Table 2. Although not strictly a petrographic property, particle shape has been included in this list because it may be influenced by texture or structure, or both.

EVALUATION OF FOULING

Fouling of ballast and resultant loss of permeability can be attributed to the introduction of fines from various sources. Research suggests that, in most cases, a majority of fines are derived from the ballast itself as a result of abrasion, impact, and physical and chemical weathering.

Depending on the prevailing environmental conditions, a significant fines component may also be introduced into the ballast as windblown dust, sand, and various organic materials. Spill from railcars can introduce a variety of contaminants; the most commonly encountered in Canadian ballasts are fine-grained coal fragments and dust. Abrasion of ties contributes fragments of wood. The use of sand to increase traction during freezing conditions can introduce a considerable amount of fine-grained material.

Most of these contaminants can be easily recognized by microscopic examination. However, identification and determination of the proportions of nonorganic fines that constitute contaminants (from nonballast sources) are problematic but can sometimes be achieved using XRD analytical techniques. An XRD scan of a fines fraction will permit identification of the major minerals present. Therefore such a scan for a sample of fines can be compared with a scan for fines derived from abrasion testing of the ballast (where no contamination would occur). Any differences in minerals between the two samples may then be attributed to contamination. A similar technique can be applied when investigating possible contamination of the ballast by fines from the subgrade material.

Success in using XRD techniques in this manner depends on there being identifiable differences in mineralogy between the ballast and the contaminant. Unfortunately, this is not always the case. A further complicating factor may be weathering of the fines fraction, which would result in the material giving a scan with characteristics different from those of the parent ballast even if no contamination had occurred.

Fines from carbonate rock ballasts can be treated with acid to determine the noncarbonate component, some of which may represent a contaminant. Because many carbonate rocks contain a proportion of noncarbonate material (commonly clays), a sample of the ballast would also have to be treated to establish the extent of the initial noncarbonate fraction before any meaningful comparisons could be made.

Prediction of the fouling potential and rate of permeability loss of a ballast is extremely difficult because of the many variable factors involved. Consideration must be given to track loading, environmental conditions, size distribution and shape of particles, mineralogy, texture and structure of the component rock types, their hardness and toughness, chemical weathering potential, and the composition of the fines fraction. Unfortunately, there is no simple formula that incorporates all of these factors, and any assessment carried out by the petrographer can only be qualitative.

The influence of track loading and particle size distribution

TABLE 2 SUMMARY OF PETROGRAPHIC PROPERTIES THAT MAY, IF PRESENT IN ABUNDANCE, RESULT IN FATALLY POOR BALLAST

Properties of Ballast Rock	Principal Deleterious Effect
Mineralogical	
General high content of very soft minerals (e.g., clays, mica, chlorite)	Rapid physical degradation, clay and fine, mica-rich fines
Argillaceous sedimentary rocks (e.g., mudstone, shale)	Rapid physical degradation, clay-rich fines
Mica-rich metamorphic rocks (e.g., slate, phyllite, schist)	Rapid physical degradation, clay and fine, mica-rich fines
Igneous with deuterically altered feldspar	Rapid physical degradation, clay-rich fines
Sulfide-rich (> about 2 to 3 percent) (e.g., pyrite, pyrrhotite)	Oxidation of sulfide results in acidic conditions promoting chemical weathering of other mineral components
Textural	
Poor consolidation (in sedimentary and volcaniclastic rocks)	Rapid physical degradation by abrasion, susceptibility to freeze-thaw
High porosity (> about 5 percent) in sedimentary rocks	Degradation by freeze-thaw and abrasion if pores large and abundant
Vesicularity (in volcanic rocks)	Degradation by freeze-thaw and abrasion
Friable texture in crystalline rocks	Rapid physical degradation by abrasion, susceptibility to freeze-thaw
Structural	
Closely spaced joints, bedding partings, foliation	Rapid physical degradation by abrasion and freeze-thaw; generation of unsuitable particle shapes
Particle shape and surface characteristics	
Smooth particle surfaces (often due to rock texture)	Poor mechanical stability
Unsuitable particle shape	Poor mechanical stability; load fracture or elongated or tabular particles.

on fouling potential is highly significant (see paper by Klassen et al. in this Record). Particle shape and particle surface characteristics also influence the rate of fines production in that, all other factors being equal, well-rounded, smooth particles will produce fewer fines than angular, rough particles. However, particles that have the former characteristics lack the interparticle friction necessary to maintain a stable track bed so certain trade-offs have to be accepted.

Mineralogy is the most important single factor influencing the rate of fouling of ballast. Simply, rock types rich in soft minerals will produce fines at a higher rate than rock composed of harder minerals. The composition of the fines fraction itself is also of importance in assessing fouling and permeability loss. Quartz-rich fines can be expected to have a low capacity for cementing and will retain permeability. Fines rich in clays and carbonates will have a higher capacity for compaction and cementing. Clay-rich fines may be derived directly from clay-rich rock types such as certain fine-grained sedimentary rocks, igneous rocks with deuterically altered feldspars, or, indirectly, the chemical breakdown of the feldspar and mica components of the fines fraction itself. Theoretically, carbonate fines could be removed from the ballast by solutioning, particularly if the water percolating through the track bed is slightly acidic. Similarly, precipitation of carbonates taken into solution from the ballast or the derived fines may be a factor contributing to cementing of the ballast. However, the extent to which these processes may occur, if at all, has not been fully assessed.

Relative hardness of different rock components making up a ballast may also be of importance in determining the compositional character of the fines fraction. In a mixture of approximately equal proportions of relatively hard and soft components, the fines will be derived dominantly from the softer rock types.

Texture and structure of ballast rock types will influence fouling indirectly because these properties play an important role in determining the effective hardness and toughness of a rock.

MONITORING OF BALLAST QUALITY

To ensure a consistently acceptable quality of material from ballast sources, it is essential that samples be examined on a regular basis by a petrographer. Even if detailed geologic mapping of the source area has been carried out, unexpected variations in the geologic setting may occasionally result in the production of poor-quality material. Typical geologic features that may result in a change in rock quality are fracture or fault zones, alteration zones, and changes in lithology. The latter is perhaps most important when dealing with layered sequences of rocks (most commonly sedimentary and metamorphic), although changes in composition can also occur in intrusive rock masses, especially at or close to the contact zones with country rock. Significant changes in material from a source may necessitate a brief field reexamination to assess the changes in geologic setting so that changes can be made in the quarrying operation.

Monitoring of ballast in use is of importance and can be achieved most cost efficiently by periodic petrographic examination. If a petrographer is familiar with the characteristics of a particular material, changes that result from its use in track can easily be identified. Because the ultimate test of any ballast is in a track, monitoring will provide useful information from which projections of the life of the ballast can be made. The data will also be of great value in assessing the performance potential of other similar materials.

CASE HISTORIES

During the ballast evaluation program carried out by CP Rail all major ballast types currently used by CP Rail were subjected to extensive petrographic examination as well as a variety of physical and chemical tests (see papers by Clifton et al. and Klassen et al. in this Record). Table 3 gives a summary of the main characteristics of these materials, some of which are discussed in greater detail later with a view to demonstrating relationships among petrographic properties, results of physical tests, and actual performance.

Kimberley Float

This material, which is waste from the Sullivan Mine in British Columbia, has been used extensively by CP Rail as main-line ballast. The principal rock type is fine-grained argillite (a mildly metamorphosed argillaceous sedimentary rock) with minor amounts of albitite (a rock consisting almost entirely of feldspar). The argillite is composed of various micaceous minerals (including clays), quartz, feldspar, tourmaline, chlorite, calcite, minor iron oxides, and accessory sulfide minerals. The latter are usually present as small disseminated crystals or aggregates making up 0.5 to 1 percent of the rock on average but occasionally as much as 5 percent. Phyrrhotite and pyrite are the dominant sulfide minerals with lesser galena and sphalerite. Calcite occurs as an original mineral constituent in chlorite-rich argillite and also as a secondary mineral filling fractures.

The mineralogy of the argillite gives Kimberley Float ballast a relatively high BSG (2.78), and its dense, fine-grained, recrystallized texture indicates a negligible porosity, which is reflected in low absorption values (0.29).

Relative proportions of the major minerals vary considerably and this is reflected directly in the effective hardness and overall durability of the rock. Argillite rich in chlorite tends to be soft ($H < 3$) because of the very low hardness of that mineral ($H = 1.5$ to 2.5). Tourmaline-rich (chlorite-poor) argillite is very hard ($H > 5$), a property attributable to the high hardness of tourmaline ($H = 7$ to 7.5). The difference in hardness is clearly apparent when track samples are examined: the softer, chlorite-rich argillite particles very quickly acquire a well-rounded outline due to abrasion and impact, whereas the tourmaline-rich particles show only a mild chipping and largely retain their original angular shapes. Some of the chloritic varieties are so soft that they become

TABLE 3 SUMMARY OF MAJOR CHARACTERISTICS OF CP RAIL BALLASTS

Material	Major Component Rock Types	AN	LAA	MA	Mg-S	Abs	BSG
Walhachin	Aphanitic basalt, basaltic tuff and breccia, andesitic tuff and breccia (some calcareous), marble	23.6	11.6	2.4	0.83	0.57	2.63
Kimberley Float	Fine-grained argillite (>90%) and albitite (<10%)	25.6-36.1	12.7-15.8	2.2-5.2	0.1-0.5	0.25-0.4	2.71-2.77
Hawk Lake	Medium-grained granodioritic gneiss (>90%), coarse-grained granite (<10%), and schist (<1%)	41.9	29.9	2.4	0.0	0.04	2.67
Uhtoff	Fine-grained limestone and dolomite	60.2	30.2	6.0	6.8	0.56	2.68
Terrebonne	Coarse-grained limestone (50%) and dolostone (50%)	90.4	33.9	11.3	7.1	0.97	2.74
Hilton	Medium-grained granite (70%), biotite gneiss (25%), and serpentine (5%)	42	22	4	2.69	0.56	2.71
Gap	Mildly recrystallized oolitic limestone	61.9	29.4	6.5	1.2	0.15	2.62
Gouvenor*	Orthoquartzite (90%), quartzite (5%), and arkose (5%)	20.7	13.7	1.4	0.1	0.4	2.57
Dunelm*	Orthoquartzite (85%), quartzite (6%), arkose (4%), and granite and gneiss (5%)	26.2	19.2	1.4	0.1	0.3	2.58
Robsart*	Orthoquartzite (85%), quartzite (4%), arkose (5%), granite and gneiss (4%), and limestone (2%)	36.0	22.5	2.7	0.1	0.17	2.60
Hardisty*	Orthoquartzite (95%), quartzite (3%), and granite and gneiss (2%)	35.4	27.9	1.5	0.2	0.97	2.59
Wheatland*	Medium- to coarse-grained gneiss (45%), dolostone (40%), and amphibolite (15%)	37.8	24.8	2.6	1.2	1.02	2.62
Duval*	Dolostone (60%), medium- to coarse-grained gneiss (30%), amphibolite (9%), and quartzite (1%)	42.9	24.9	3.6	1.2	1.02	2.62
Bearspaw*	Orthoquartzite (57%), lithic sandstone (22%), quartzite (3%), limestone (12%), and siltstone (6%)	47.2	22.7	4.9	2.34	0.96	2.53
McKague*	Dolostone (50%), gneiss (40%), schist (2%), quartz sandstone (2%), amphibolite (5%), and limonite concretion (1%)	44.6	28.1	3.3	0.06	0.73	2.69
Slawa*	Medium- to coarse-grained gneiss (55%), calcareous sandstone (8%), quartz sandstone (15%), limonite concretions (4%), amphibolite (4%), and dolostone (3%)	60	37.5	4.5	0.5	0.4	2.54

Note: AN = abrasion number, LAA = Los Angeles abrasion, MA = mill abrasion, Mg-S = magnesium soundness, Abs = absorption, BSG = bulk specific gravity. Asterisk denotes crushed pebble or cobble ballast; all others are crushed quarried rock.

subrounded merely as a result of crushing and transportation. Mill abrasion losses for the ballast samples typically range from 2.2 to 5.2 percent.

The argillite is a moderately tough rock, a quality that does not vary greatly with changes in mineralogy (LAA losses range from 12.7 to 15.8 percent for fresh material). The rock has a weakly developed foliation that results in some elongation of particles on crushing, but this is not a prominent feature and apparently has no significant negative influence on toughness or stability. The most important factor limiting toughness is the overall medium hardness of the material.

The importance of effective hardness in influencing the performance potential of a ballast such as this, composed of fine-grained rock, is well illustrated by the relationships between abrasion test results and hardness as estimated by petrographic examination. During the course of examining Kimberley Float ballast from various track sections and from the source stockpile, a semiquantitative estimate of hardness was made simply by determining the proportion of particles with hardness values of less than 5 on Mohs' scale. Graphic plotting of the percentage of soft components ($H < 5$) against abrasion number ($LA + 5\ MA$) shows a fairly crude but quite definite correlation (Figure 1). By drawing on data on the durability of the materials as indicated by their track life and degradation characteristics, tentative subdivisions (based on AN) that indicate suitability as ballast have been indicated on the plot. Although there is a fair amount of scatter in the distribution of data points, it is apparent that, when a relationship such as this has once been established for a particular ballast material, the petrographer should be able

to make useful predictions of abrasion test results and performance in track, even without having abrasion test results in hand. This example also demonstrates that the results of abrasion tests and durability in track are determined to a great extent by petrographic characteristics.

This exercise also provided insight into another important aspect of ballast testing. Misleading abrasion results can be obtained from materials that have been in service in track. These data may not be directly comparable with abrasion data derived from fresh materials from the source deposit. Petrographic examination of Kimberley Float ballast from Mile 52.2 of the Mountain Subdivision (CP Rail) indicated a very low content of soft components, an observation that is consistent with the exceptional durability of this material in track. However, initial abrasion test results indicated an anomalously high AN (Sample KF-1 in Figure 1), which was at odds with the petrographic data. Because they had been in the track for 17 years, the ballast particles had developed alteration mantles as well as acquired coatings of oil, grease, and adhering fines. Before further material from the same track section was tested, the samples were treated with a solvent to remove the oil and grease and the particles were scrubbed with a wire brush to remove at least the looser weathered material. The results of samples treated in this manner are shown in Figure 1 (Samples KF-2, KF-3, and KF-4), and it is apparent that they fall within the limits of the general distribution of points, whereas if they had been tested in an untreated state they could have been expected to plot close to Sample KF-1. It is not likely that the treatment restored the Mile-52.2 samples completely to their original condition, so by using the plot it can be estimated that a reasonable absolute minimum AN for the original material placed in this track section would be about 26.5. This study illustrates clearly the danger of comparing abrasion test results obtained from fresh material with those obtained from material that has been used in track. If such comparisons are to be made, due consideration must be given to the already degraded state of the used material.

The study of Kimberley Float ballast also provided clear evidence for the deleterious effects of sulfide minerals, which create an acidic environment in the ballast on oxidation. Evidence for this could be found in iron oxide spots and coatings, thin mantles of clay-rich alteration products, and

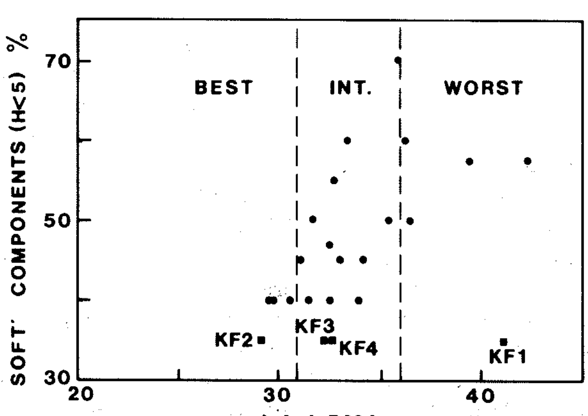

FIGURE 1 Plot of soft components versus AN.

sulfate deposits on fragment surfaces. It should also be emphasized that chemical weathering and physical breakdown by abrasion and impact operate hand in hand; the weathered mantles will be soft, allowing easy removal by physical processes and thus exposing further fresh argillite to chemical attack. It was observed that ballast with a low sulfide content (< 0.5 percent) showed little or no sign of chemical weathering whereas material with high sulfide contents (2 to 3 percent and higher) clearly displayed significant chemical breakdown.

The durability of Kimberley Float ballast has been extremely variable, and, in general, that placed in track at an early stage in the use of this material (early 1960s) has performed far better than that used during the 1970s. The reason for this difference becomes clear when the major petrographic characteristics are considered. The earlier material has a relatively high overall hardness and is low in sulfides (< 0.5 percent) whereas the later material, although variable, is always softer and has a higher average sulfide content (2 to 3 percent). Possible reasons for this change in quality of the material over the years can only be guessed at, but certainly it reflects a change in some aspect of the mining operation or of the rock being quarried. Whatever the reason, such changes in material quality, which may necessitate unexpected expenditure in track maintenance, should not go unnoticed. This emphasizes the importance of monitoring ballast sources by regular petrographic examination.

During petrographic examination of Kimberley Float ballast, it was noted that samples from immediately above the subballast in certain track sections contained a relatively high proportion of fines. A study was conducted in an attempt to determine if these had been derived entirely from the ballast or if the fines-rich subballast had also contributed fines by upward migration. Normal petrographic procedures (using a microscope) were not capable of making a satisfactory discrimination so the minus No. 200 fractions were subjected to XRD analysis. The XRD scans indicated that the mineral assemblages in the ballast and subballast fine fractions were quite similar and no clear-cut distinction could be made on this basis alone. However, careful analysis of the XRD traces indicated a definitely greater abundance of mica in the subballast. Mica was present in the overlying ballast fines but in lesser proportion. These proportions were found to be constant throughout all levels of the ballast, which indicates that there had been no significant mixing or contamination of fines in the lower ballast levels (which would have been indicated by an enrichment of mica). Furthermore, the mica in the subballast produced a well-defined, sharp peak on the XRD trace whereas the mica peaks in the ballast fines were broad and diffuse. These differences are not entirely due to the greater abundance of fines in the subballast; they probably also indicate a difference in crystalline character.

On the basis of this evidence, it is suggested that the high proportion of fines concentrated immediately above the subballast can be attributed to a downward migration of material derived mainly by abrasion in high levels of the ballast. Although the results obtained were not entirely conclusive, the study was of value in that it pointed out the feasibility of XRD methods for elucidating problems related to the source of fines.

Walhachin

Ballast from the Walhachin Quarry in central British Columbia is made up of a variety of rock types, primarily volcanogenic affinities. The quarry is located within the Nicola Group (Upper Triassic age). The volcanic rock units have been metamorphosed and strongly deformed with steeply dipping and folded beds and considerable faulting and fracturing. Recent redevelopment of the Walhachin Quarry involved a program of geologic mapping, drilling, petrographic analysis, and physical testing of most representative rock types and geotechnical evaluation and quarry design (see paper by Clifton et al. in this Record).

Six major groups of rock types can be distinguished in the quarry and from drilling operations in the immediate vicinity. All of these types have appeared as ballast components at some time or another, and the relative proportions have been dependent on which particular part of the quarry the material was taken from. Because these rock types vary considerably in their durability characteristics, it follows that variation in their relative proportions has resulted in corresponding variation in the overall quality of the material (which has, nevertheless, remained within acceptable limits). Such variations emphasize the importance of having detailed geologic information on the source and monitoring ballast source material, particularly if the geology of the source is complex and compositionally heterogeneous. Differences in durability of the various rock types can generally be accounted for by consideration of their petrographic characteristics.

Basaltic Tuff and Breccia

These rock types consist of angular fragments of aphanitic basaltic rock set in a matrix of identical, but finer, material. The rocks are extremely well indurated and generally very hard; they are also somewhat brittle and often break with a conchoidal fracture. Plagioclase feldspar, a relatively hard mineral (H = 6), is an important primary constituent and metamorphism has also resulted in the development of secondary minerals of which epidote (as much as 20 percent) and magnetite (as much as 25 percent) are prominent. Both of the latter are relatively hard minerals (H = 6 to 7 and 5.5 to 6.5, respectively) and are primarily responsible for the excellent abrasion characteristics of these rock types (Table 4). These minerals have a high resistance to chemical breakdown, which further enhances their overall durability. One negative aspect of these rock types is the common presence of irregular fracturing (due to brittleness) that, although fairly widely spaced (> 0.5 in.), does sometimes result in relatively high LAA- and Mg-S-values compared with relatively unfractured samples of the same type (Table 4).

Aphanitic Basalt

This extremely fine-grained rock has mineralogy similar to that of the basaltic tuff and breccia and as a result is very hard and tough.

Calcareous Tuff and Breccia

These rock types are composed of angular fragments of andesite, set in a matrix of finer but similar material, plus variable amounts of calcite (as much as 30 percent). Epidote and garnet are prominent secondary minerals (20 to 70 percent). The durability of this rock, as indicated by abrasion test data, is variable depending on the proportions of the constituent minerals. It is limited primarily by the calcite, a relatively soft mineral (H = 3) that is prone to cleavage fracture. These properties result in rocks of only medium hardness and AN (Table 4). The significant effect of weathering on the performance of ballast is well displayed by a weathered sample of this rock type that returns a very high AN (89.07) and an extremely high Mg-S (27.01).

Limestone and Limestone Breccia

These are relatively uncommon rock types that occur as discontinuous lenses within the volcanic sequence. The

TABLE 4 ABRASION AND Mg-SOUNDNESS CHARACTERISTICS OF SOME TYPICAL MAJOR ROCK TYPES FROM THE WALHACHIN QUARRY (CP RAIL)

Rock Type	LAA	MA	AN	Mg-S
Basaltic tuff	11.33	1.63	19.48	1.42
Basaltic tuff and breccia	15.40	2.35	27.15	1.97
Basaltic tuff and breccia (highly fractured)	20.59	3.93	40.24	4.00
Limestone breccia (recrystallized)	33.56	7.88	72.96	0.96
Calcareous tuff and breccia	13.90	5.57	41.75	4.67
Calcareous tuff and breccia (strongly weathered)	29.52	11.91	89.07	27.01
Intermediate (andesitic) tuff and breccia	18.90	5.71	47.45	6.70
Coarse intermediate tuff and breccia	16.06	5.52	43.66	5.91

Note: LAA = Los Angles abrasion, MA = mill abrasion, AN = abrasion number, Mg-S = magnesium soundness

limestone is a fine- to medium-grained crystalline rock and the breccia consists of fragments of this material set in a matrix that ranges from nearly pure carbonate to fine volcanic rock fragments. Both types have been recrystallized. As ballast components, these are undesirable materials because they have high LAA- and MA-values (Table 4) that can be attributed to the softness of the calcite, its prominent mineral cleavage, and its weakness as a binding agent in the breccia. Notably, the Mg-S-value is very low due to the dense, recrystallized, and unfractured state of the rocks.

Intermediate (andesitic) Tuff and Breccia

These are highly variable rock types composed of fragments of volcanic rock set in a matrix of finer volcanic rock fragments, feldspar crystals, epidote, calcite, magnetite, and minor garnet. Generally these materials are of medium to high hardness and toughness (estimated), but some of the finer tuffaceous varieties have a relatively high calcite content and display bedding; both of these properties result in moderately high abrasion losses (Table 4).

Coarse Andesitic Breccia

This rock type differs from that described previously in that it is coarser grained and has a carbonate fragment component. Moderate MA losses that characterize this material (Table 4) are due to the overall medium hardness (mineralogy and a partly altered condition), and the low LAA-values can be explained in terms of its well-consolidated and relatively unfractured nature. High Mg-S-values can probably be attributed to the presence of small solution cavities (removal of calcite).

Prairie Gravels

Pleistocene glacial gravel deposits are frequently used as ballast sources in the Canadian prairies region. These gravels are usually composed of a mixture of rock types, and common major components are quartz sandstone (or orthoquartzite), granitic-granodioritic gneiss, dolostone, limestone, granite, and amphibolite. Relative proportions of these vary depending on the source, but invariably one or more of the first three rock types mentioned are dominant, and the latter types are subordinate constituents (Table 3).

Minor components (usually < 10 percent) that may be present are mudstone, shale, siltstone, limonitic concretions, calcareous sandstone, schist, arkose, quartzite, and various meta-volcanic rocks. These minor constituents are important in that all except the last three types mentioned are of very poor quality and their presence may be critical in evaluating the material for ballast purposes. Only a few percent of a very soft, clay-rich rock, such as mudstone, will render the material unacceptable as ballast because there will be a rapid initial buildup of fines and loss of permeability.

In addition to mineralogical criteria, particle shape and particle surface characteristics are important considerations when evaluating glacial gravel ballasts. Before crushing, a vast majority of particles are well rounded with generally smooth surfaces (i.e., water worn before deposition). Crushing fractures many of the pebbles and cobbles, thereby reducing the proportion of rounded surfaces and, on the average, increases the angularity of the particles. However, depending on the original particle size distribution of the material, the crushed product will always contain a certain proportion of particles that retain their original well-rounded outlines (small enough to be unaffected by crushing) and particles that have only one or two new fracture faces with a dominance of well-rounded and smooth surfaces. Even a moderate content of particles with these shape characteristics will render the material mechanically unstable. Consequently, shape factor testing is strongly recommended when evaluating this type of ballast.

As a result of their initially well-rounded and approximately spheroidal shape characteristics, the pebbles in these materials display a strong tendency to fracture (during crushing) in such a manner as to produce particles that have marked elongated or flattened shapes, or both; these are particularly abundant in the smaller size fractions ($< 3/4$ in.). Such particles are highly susceptible to load fracture in track, which further limits their applicability. Although largely independent of rock type, the tendency to produce elongated or flattened particle shapes is more prominent in the more brittle rocks such as orthoquartzite.

The nature of the major components of prairie gravels indicates that these materials will not constitute high-grade ballast. The quartz sandstone (arenite) is a clean, "mature" variety composed almost entirely of quartz grains that are well cemented by secondary silica occurring as grain overgrowths. This is a very hard rock type and ballasts composed dominantly of it produce, as a consequence, very low MA losses (1.4 percent). LAA losses are low to moderate (13.7 to 27.9 percent). It is extremely resistant to chemical weathering and its high durability in track is indicated by only a mild chipping of particle edges. The rock is usually dense, but rarely a microporosity is present; this is indicated by high absorption values and otherwise detectable only by thin-section examination. However, in spite of these excellent qualities, fragments and pebbles of this rock type possess very smooth surfaces that result in a high degree of mechanical instability.

The gneiss component ranges from fine to coarse in grain (crystal) size and is composed of feldspar and quartz as major minerals with lesser ferromagnesian constituents (mainly biotite mica or amphibole, or both). The gneisses are moderately tough and moderately hard rocks with a coarse foliation that does not significantly influence the fracture pattern on crushing. Provided that the proportion of original well-rounded surfaces on the particles is low, ballasts composed dominantly of this rock type will have acceptable mechanical stability because of the generally rough fracture surfaces. Cleavage fracture in the constituent feldspar crystals is a major factor limiting toughness and, to a lesser extent,

hardness. In track the gneiss particles become rounded but are not greatly modified in shape when subjected to light loading.

Ballasts composed dominantly of dolostone tend to have moderate toughness (Table 3) and low hardness; the primary limiting factor is the softness of the constituent mineral dolomite. Cleavage fracture in the dolomite crystals may also be an important factor, particularly in the more coarsely crystalline varieties. Much of the dolostone has a porosity that may constitute up to 10 percent of the rock volume making it susceptible to degradation by freeze-thaw. The low resistance of carbonate rock types to abrasion is indicated by the considerable rounding of particles that frequently occurs by attrition during crushing, and in track they quickly acquire subrounded to rounded shapes.

Of the other major components of prairie gravels, granite displays behavior that is similar to that of the gneiss. Limestone is similar to, but even softer than, dolostone. Amphibolite is a rock type composed mainly of the mineral amphibole and is a tough, moderately hard material. Of all of the major constituents, gneiss (and granite) is the best because it offers the highest degree of mechanical stability combined with moderate toughness and hardness (Table 3).

Absorption values for prairie ballasts are generally fairly low (< 1.0) and acceptable for the rating assigned on the basis of other characteristics. Occasional high absorption is usually due to one or more of the following: intergranular porosity in the sandstone, porosity in the dolostone, microfractures in the dolostone, and intercrystalline and cleavage partings in the gneiss.

BSG is variable, depending on the relative proportions of the major components. Materials rich in quartz sandstone or gneiss have low BSG on the order of 2.6 whereas those rich in dolostone may range up to 2.7 or higher.

CONCLUSIONS

Petrographic evaluation of rock ballast, in spite of being a largely subjective process, can provide useful assessments of performance in track, qualitatively predict the results of physical tests, provide rational explanations of test results, identify potential problems in materials intended for use as ballast, and provide reasons for failure of degraded material from track sections.

The performance characteristics of a rock ballast will be determined essentially by mineralogical, textural, and structural petrographic properties, usually in that order of importance.

Effective hardness is judged to be the single most critical factor in determining the durability of ballast. It depends primarily on mineralogy and texture, and to a lesser extent on structure, of the ballast components. These properties can be determined and effective hardness estimated or semiquantitatively measured, which permits useful assessments of ballast performance potential to be made.

Toughness of a ballast will also depend on structural, textural, and mineralogical properties, the relative importance of which is variable. Toughness can be qualitatively determined but cannot be related to a scale as hardness can.

Particle shape and surface characteristics, both critical factors influencing the mechanical stability of ballast, will depend to a great extent on rock structure and texture, respectively.

Chemical weathering of ballast particles will not usually be a prime cause of failure, although it may be a contributing factor. The potential for chemical breakdown of the derived fines component is, however, much higher and represents a significant factor in ballast evaluation.

Petrographic properties that may cause a ballast to be of fatally poor quality fall into three principal categories: mineralogical properties, such as alteration, high content of clay, mica, and sulfides; textural properties, such as poor consolidation, high porosity, and friability; and structural weaknesses, such as finely spaced foliation, joints, and bedding planes.

Petrographic analysis can provide quite specific information on the nature and source of derived fines, especially if the more sophisticated analytical techniques can be applied. X-ray diffraction and chemical analytical methods have great potential in this respect.

Petrographic analysis constitutes the most appropriate method for monitoring the quality of ballast from sources and the degradation characteristics of ballast from track.

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Appendix: CP Rail Specification for Ballast

Revised January 1, 1984.

SECTION I: EVALUATING PROCESSED ROCK, SLAG AND GRAVEL BALLAST SOURCES

1. Scope

This specification covers the requirements for evaluating properties of rock, slag and gravel for processed ballast.

2. Purpose

This specification is intended to identify suitable supply sources and to compare alternative sources for processed ballast. This specification shall also be used in conjunction with *Specification for Ballast — Section II, Processing Rock, Slag and Gravel Ballast,* to monitor the properties of material processed as ballast.

3. General Requirements

Processed ballast shall be crushed rock, nickel slag or crushed gravel, composed of hard, strong and durable particles, free from injurious amounts of deleterious substances and conforming to the requirements of this specification.

4. Ballast Material Tests and Track Ballast Standards

(a) The ballast material tests described in this specification shall be performed on representative samples.

(b) The petrographic analysis under Appendix A shall be used in conjunction with other ballast material tests listed in this section.

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

(d) The results of the physical property tests for stability listed below must meet the applicable Track Ballast Standards given in Table 1.

Bulk Specific Gravity	ASTM C127
Fractured Particles	Appendix A

(e) The results of the material quality tests for resistance to weathering listed below should meet the applicable track ballast standards given in Table 1.

Magnesium Soundness	ASTM C88 Five cycle on Ballast Grading 3
Absorption	ASTM C127 on Ballast Grading 3

(f) The results of the material quality tests for abrasion listed below must meet the applicable Track Ballast Standards given in Table 1.

Los Angeles Abrasion	ASTM C535 Grading 3
Mill Abrasion	Appendix A
Abrasion Number	Appendix A

(g) The material will be sampled and sized according to the following methods of test.

Sampling Aggregates	ASTM D75
Wire Cloth Sieves	ASTM E11
Sieve or Screen Analysis of Fine and Coarse Aggregates	ASTM C136
Materials Finer than No. 200 Sieve in Mineral Aggregates by washing	ASTM C117

(h) The material shall be processed to meet the appropriate grading of the Track Ballast Standards given in Table 1.

Alternative specifications and gradings may be used for special conditions, but only where specially authorized by the Chief Engineer.

5. Selection of Ballast Material

Materials meeting the applicable standards for the ballast material tests contained in this specification shall be compared. The ballast source selected shall be the most economical material based on the cumulative tons of rail traffic.

TABLE 1 TRACK BALLAST STANDARDS

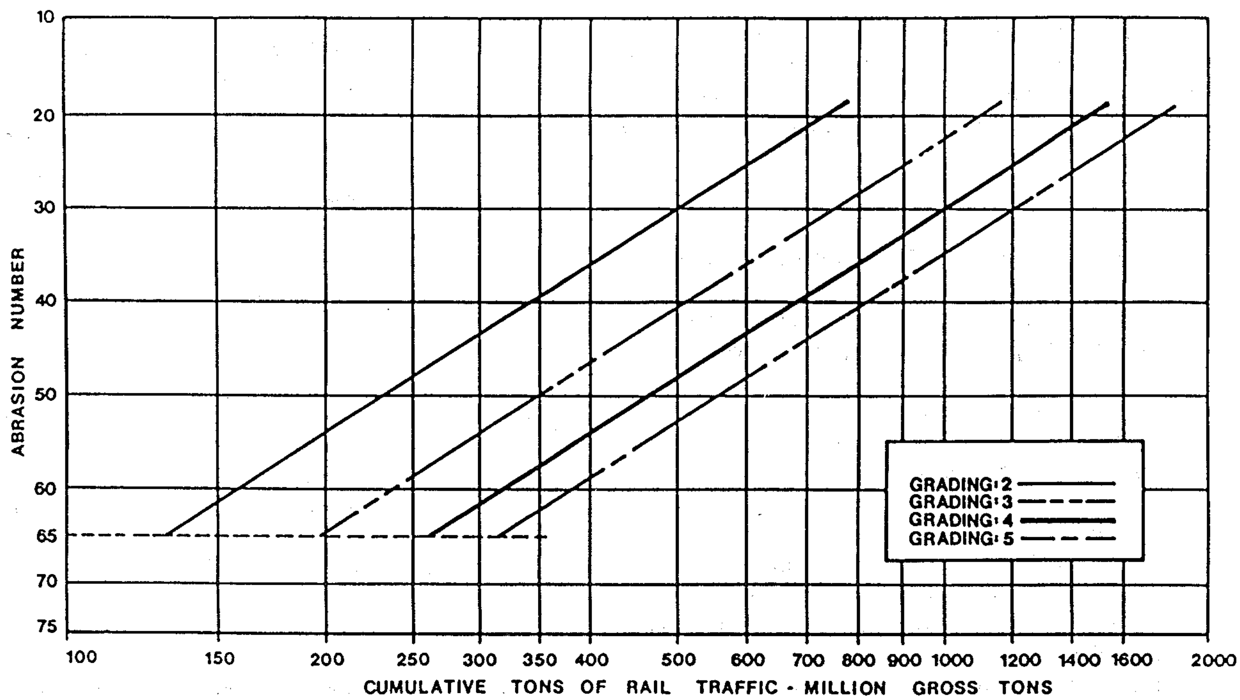
Track Classification	Primary Main Line CWR	Primary Main Line Jointed	Secondary Main Line	Branch Line Important	Branch Line Minor
Stability - minimum allowable values given					
Bulk Specific Gravity	2.60	2.60	2.60	2.60	2.60
Fractured Particles - percent					
Ballast Grading					
2	-	70	60	60	60
3	80	75	65	60	60
4	90	85	75	65	65
5	100	-	-	-	-
Weathering - maximum allowable values given					
Magnesium Soundness	1	1.5	3	3	3
Absorption	0.50	0.75	1	1	1

Abrasion

Los Angeles Abrasion shall be less than 45
Mill Abrasion shall be less than 9
Abrasion Number shall be less than 65; also shall be less than Abrasion Number for the cumulative tons of rail traffic for a 20-year period from Plan X-10-16-233, and should be less than Abrasion Number for the cumulative tons of rail traffic for a 30-year period from Plan X-10-16-233.

Ballast Grading	Maximum Size Inches	2 1/2"	2"	1 1/2"	1"	3/4"	1/2"	3/8"	No.4	No.200
		Percent By Weight Finer Than Specified Sieve								
2	2		100	90-100	70-90	50-70	25-45	10-25	0-3	0-2
3	2		100	90-100	70-90	30-50	0-20	0-5	0-3	0-2
4	2		100	90-100	20-55	0-5			0-3	0-2
5	2 1/2	100	90-100	35-70	0-5				0-3	0-2

Ballast gradings 2 and 3 shall be used for crushed gravel.
Ballast grading 4 shall be used for crushed gravel, crushed rock or slag.
Ballast grading 5 shall be used for crushed rock or slag.



NOTE: DEVELOPED FOR TANGENT TRACK WITH 7 IN. OF BALLAST BELOW TIE. A SMALL AMOUNT OF CONTAMINATION FROM OUTSIDE SOURCES HAS BEEN TAKEN INTO CONSIDERATION.

CAUTION: EXCESSIVE HANDLING OF BALLAST MATERIALS IN THE UPPER RANGE OF ABRASION NUMBERS MAY GENERATE FINES WHICH WILL REDUCE THE APPLICABLE CUMULATIVE TONS OF RAIL TRAFFIC.

CP Rail

BALLAST ABRASION NUMBER vs CUMULATIVE TONS OF RAIL TRAFFIC FOR VARIOUS BALLAST GRADINGS

X-10-16-233

OFFICE OF THE CHIEF ENGINEER.
MONTREAL, ~~FEB. 15, 1982~~ JAN. 1, 1984 GRADING: 1 DELETED

FIGURE 1 Plan X-10-16-233.

6. Acceptance of Supply Source

(a) All evaluation results shall be forwarded to the Chief Engineer.

(b) A summary sheet will be forwarded to the Chief Engineer summarising the economics of the sources considered.

(c) The Chief Engineer must approve the source prior to its acceptance.

7. Monitoring of Processed Ballast

(a) Representative samples of processed ballast shall be obtained at regular intervals during processing, and tested in accordance with this specification.

(b) A summary of the test results shall be forwarded to the Chief Engineer at the close of each years processing of ballast.

Signed
Engineer of Track
and
Chief Engineer

This specification supersedes specification dated February 15, 1982.

APPENDIX A TO EVALUATING PROCESSED ROCK, SLAG AND GRAVEL BALLAST SOURCES

Petrographic Analysis

Petrography is the systematic description of rocks in hand specimen and thin section.

An experienced petrologist shall perform a petrographic analysis on the material. The megascopic features of the material shall be obtained from visual inspection aided by standard material identification and classification techniques. The microscopic features shall be obtained from inspection of thin sections of the material under a petrographic microscope.

The information obtained from the petrographic analysis on representative block samples and/or representative samples crushed to the various ballast sizes shall be documented under the following headings.

(a) Rock types retained on individual sieves including a description for layman where necessary.

(b) Mineralogy of rock types including proportions.

(c) Texture including grain size, shape, orientation, mutual relationships and matrix material.

(d) Structure identifying bedding planes, fracture planes and cleavage planes and foliation planes.

(e) Mechanical properties including hardness, strength and brittleness, type of fracture, shape and roundness.

(f) Chemical properties defining existing chemical weathering and potential chemical weathering.

(g) Properties of fines including shape, permeability, and susceptibility to solution and precipitation.

(h) Estimated test results including explanations.

(i) Special tests required including explanations.

(j) Summary of remarks including recommendations.

Fractured Particles Test

The Fractured Particles Test is as follows:

A representative sample is obtained and sized using current ASTM methods of test. From each coarse aggregate fraction representing five percent or more of the submitted sample, split a representative portion into samples, of within 10 percent of the weight specified below.

Sieve Passing	*Sieve Retained*	*Weight in Pounds ±10 Percent*
2"	1 1/2"	13.0
1 1/2"	1"	6.5
1"	3/4"	3.5
3/4"	1/2"	2.25
1/2"	3/8"	1.0
3/8"	No. 4	0.75

Each sample shall then be separated into fractured and non fractured particles according to the following criteria.

A fractured particle shall be a particle with three or more fractured faces. Each of the fractured faces on the fractured particle must have a freshly exposed rock surface with a maximum dimension of at least one third the maximum particle dimension and a minimum dimension of 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 as separate fractured faces.

Particles which do not meet the above criterion will be classified as non fractured particles.

The fractured particles for each sample will be calculated as a percentage by the following formula.

Fractured Particles = Weight of fractured particles/Original Weight × 100

Mill Abrasion Test

The Mill Abrasion Test procedure is as follows:

A representative sample is obtained and sized using current ASTM Methods of Test. From the coarse aggregate, split a

representative portion into a sample consisting of 3.3 lb. passing the 1 1/2 in. sieve and retained on the 1 in. sieve plus 3.2 lb. passing the 1 in. sieve and retained on the 3/4 in. sieve. The sample shall be washed and oven dried in accordance with the Los Angeles Abrasion procedure. The sample will then be placed in a 1 gallon, 9 in. external diameter porcelain ball mill pot, along with 6.6 lb. of distilled water. The mill pot shall be sealed and rotated at 33 RPM for a total of 10,000 revolutions (five hours). The sample shall then be wash-sieved through a No. 200 sieve and oven-dried before weighing. Mill Abrasion shall be calculated as a percentage loss in weight by the following formula.

Mill Abrasion = Loss in weight/Original weight × 100

Abrasion Number

The Abrasion Number is a number calculated with the results of the Los Angeles Abrasion Test and Mill Abrasion Test given in this specification. The Abrasion number shall be calculated by the following formula.

Abrasion Number = Los Angeles Abrasion + 5 × Mill Abrasion

SECTION II: PROCESSING ROCK, SLAG AND GRAVEL BALLAST

1. Scope

This specification covers the requirements for material, grading, handling, stockpiling, inspection, measurement and payment for processed ballast.

2. Material

The material identified by location, description and/or properties consistent with *Specification for Ballast — Section I, Evaluating Processed Rock, Slag and Gravel Ballast, Sources* shall be processed as ballast.

3. General Requirements

Processed ballast shall be crushed rock, nickel slag or crushed gravel, composed of hard, strong and durable particles, free from injurious amounts of deleterious substances and conforming to the requirements of this specification.

4. Processing Requirements

(a) Grading
(1) The processed ballast shall be sampled, sized and tested in accordance with the following current ASTM Methods of Test.

Sampling Aggregates	ASTM D 75
Wire Cloth Sieves	ASTM E 11
Sieve or Screen Analysis of Fine and Coarse Aggregates	ASTM C 136
Materials Finer than No. 200 Sieve in Mineral Aggregates by Washing	ASTM C 117
Unit Weight of Aggregate	ASTM C 29 Jigging procedure

(2) The processed ballast shall conform to one of the following Ballast Gradings as specified by the Engineer.

Ballast Grading	Maximum Size Inches	Percent By Weight Finer Than Specified Sieve 2 1/2"	2"	1 1/2"	1"	3/4"	1/2"	3/8"	No.4	No.200
2	2		100	90-100	70-90	50-70	25-45	10-25	0-3	0-2
3	2		100	90-100	70-90	30-50	0-20	0-5	0-3	0-2
4	2		100	90-100	20-55	0-5			0-3	0-2
5	2 1/2	100	90-100	35-70	0-5				0-3	0-2

(b) Fractured Particles
(1) The processed ballast shall be tested in accordance with the Fractured Particles Test given in Appendix A.
(2) The processed ballast shall conform to the percent fractured particles specified by the Engineer, consistent with the following, for each size of coarse aggregate tested.

Ballast	Primary Main Line		Secondary	Branch Line	
Grading	CWR	Jointed	Main Line	Important	Minor
2	-	70	60	60	60
3	80	75	65	60	60
4	90	85	75	65	65
5	100	-	-	-	-

5. Handling

Processed ballast shall be handled in such a manner that it is kept clean and free from segregation.

6. Stockpiling

Stockpiling of processed ballast will only be permitted at a designated site with an adequately constructed base. The processed ballast shall be stockpiled in layers, dumping over the sides of the pile will not be permitted. Stockpiling of processed ballast by pushing or dozing will not be permitted. Crawler type equipment should not be used on the processed ballast stockpile. Travel distances of rubber tired equipment on the processed ballast stockpile should be kept to a minimum, and shall not exceed 300 yards.

7. Inspection

The production of processed ballast shall be monitored to ensure the conditions of this specification are met. Samples shall be tested at least once per processing shift or every 1000 tons of production.

8. Measurement

The quantity of processed ballast shall be measured by weight on a platform scale equipped with an automatic printout. The scale shall be tested and sealed by the Standards Division, Weights and Measures Branch, Department of Trade and Commerce, Government of Canada.

When less than 100,000 tons of material are to be processed as ballast, an alternative method of measurement may be specified by the Engineer.

The quantity of prepared ballast shall be monitored continuously and the quantity recorded.

9. Payment

Prepared ballast will be paid for according to the actual measurement by weight or volume.

Signed
Engineer of Track
and
Chief Engineer

This specification supersedes Specification dated February 15, 1982.

APPENDIX A TO PROCESSING ROCK, SLAG AND GRAVEL BALLAST

Fractured Particles Test

The Fractured Particle Test is as follows:

A representative sample is obtained and sized using current ASTM Methods of Test. From each coarse aggregate fraction representing five percent or more of the submitted sample, split a representative portion into samples, of within 10 percent of the weight specified below.

Sieve Passing	*Sieve Retained*	*Weight in Pounds* ±10 Percent
2"	1 1/2"	13.0
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Particles which do not meet the above criterion will be classified as non fractured particles.

The fractured particles for each sample will be calculated as a percentage by the following formula.

Fractured Particles = Weight of fractured particles/Original Weight × 100