Application of Petrographic Analysis to Ballast Performance Evaluation

DEBRA L. BOUCHER AND ERNEST T. SELIG

In this paper is presented an interpretation of ballast performance test results that uses the information obtained from petrographic analysis of ballast material to help assess the importance of this technique as a means of evaluating ballast. Fourteen ballast materials were used in this study. These were tested in a special ballast box apparatus under differing conditions of equivalent wheel load, material gradation, and number of load cycles. Mill abrasion and ballast cementing tests were also performed on these materials and Los Angeles abrasion values were obtained from the ballast suppliers. Identification of the mineral composition and texture of the ballast material, as well as inherent planes of weakness such as foliation and cleavage, can be accomplished using petrographic analysis. With a few exceptions, petrographic analysis was found to provide a reasonable explanation of the performance of the ballast materials in each of the tests. Performance of ballast in track is a function of field conditions and particle shape and grading as well as of factors identified by petrographic analysis. Thus petrographic analysis is not yet sufficient to predict performance—but neither are commonly used index tests. However, appropriate research involving field observations as well as laboratory testing has the potential to provide a significant improvement in ballast performance prediction using petrographic analysis as an important tool. Such analysis should be performed by a petrographer with experience in railroad applications.

Performance of railroad ballast as used in this paper is represented by its ability to hold track geometry under repeated wheel loading and existing environmental conditions. Important mechanical properties include (a) strength and resiliency of the assembly of particles and (b) resistance to breakage and abrasion of the individual particles.

Thus, in an evaluation of a material's performance as a ballast, gradation, particle shape, and rock type, including texture and composition, must be considered. However, if all factors but rock type were held constant, there would still be variability of performance because different rock types have different physical properties. A ballast box test was developed at the University of Massachusetts at Amherst (UMass) to investigate the effect of all of these factors. In addition, several index tests were used to measure the effect of rock type. These were mill abrasion tests and ballast cementing tests, which were performed at the university, and Los Angeles abrasion tests conducted by the suppliers of the ballast materials.

D. L. Boucher, Parsons, Brinckerhoff, Quade and Douglas, Inc., One Penn Plaza, New York, N.Y. 10119. E. T. Selig, Department of Civil Engineering, University of Massachusetts, Amherst, Mass. 01003.

Previous experience with petrographic analysis for aggregate evaluation has suggested that knowledge of the mineral composition and texture of the rock, as well as physical properties such as bedding planes, *foliation* (terms in italics are defined in the Glossary), and porosity, would be useful in understanding the behavior of ballast. Thus identification of rock type and characteristics on the basis of petrographic analyses, including hand-sample and thin-section techniques, has been incorporated into the UMass ballast testing program. The purpose is to assist in the evaluation of results obtained from these ballast performance tests and to help establish the value of using hand-sample and petrographic analysis in predicting ballast performance. The results of this recent research are summarized in this paper.

CURRENT APPLICATIONS OF PETROGRAPHIC ANALYSIS

The value of petrographic evaluation as a means of assessing or predicting, or both, behavior of an aggregate has been long recognized by the concrete industry. Techniques for evaluating aggregate for use in concrete and for examining hardened concrete have been established by ASTM in standards C 295 (for aggregate) and C 856 (for hardened concrete). The purposes of this petrographic examination are (a) to determine the physical and chemical properties of the material that will have a bearing on the quality of the material for the intended purpose; (b) to describe and classify the constituents of the sample; and (c) to determine the relative amounts of the constituents of the sample, which is essential for the proper evaluation of the sample, especially when the properties of the constituents vary significantly. The value of the petrographic evaluation is said to depend to a large extent on the ability of the petrographer to correlate data provided on the source and proposed use of the material with the findings of the petrographic examination.

A method of numerical evaluation of the quality of aggregates used for concrete on the basis of petrographic analysis was developed by the Materials and Research Section of the Department of Highways (DOH) of Ontario (*1*). This method was based on extensive studies of field performance of aggregate used in concrete and bituminous pavement. With this method, a sample of aggregate is first examined for composition (i.e., rock type or types) and then assigned a number (factor) based on experience with that or similar rock types and their observed field performance. Rock types considered to be excellent are given values close

to 1 and those considered to be poor approximately 6. This number is then multiplied by the percentage of each rock type in the aggregate sample, which gives a weighted value. The Petrographic Number (PN) for an aggregate sample is the sum of the weighted values of all components. This number is used as a quality rating for that sample. Limits have been set for acceptable PNs for various uses of aggregate.

After several years of applying this method in the prediction and evaluation of aggregate performance, the DOH of Ontario drew several conclusions (*1*):

1. Petrographic analysis is the most significant of all quality tests. The evaluation is based on actual performance and considers both the physical and chemical properties of the aggregate.
2. Petrographic analysis is the shortest test when time is an important consideration.
3. The results were found to be fairly reliable and to provide a better appraisal of aggregate performance than either abrasion or absorption alone.
4. The technique is adaptable to both the field and the laboratory.
5. The method can be used reliably to maintain the quality of an aggregate from a previously tested and known source.

Raymond (*2*) suggested that petrographic analysis is of major value in the selection of a suitable quarry for ballast and that it can also be useful for prediction of the shape and permeability of the components of future ballast breakdown (i.e., the fines generated by breakage and abrasion of the ballast).

Canadian Pacific Rail (CPR) has included petrographic analysis as a part of their standard ballast specification (*3*). The CPR requirements for the petrographic analysis of potential ballast include

- Description of rock types, including mineralogy, texture, and structure;
- Description of mechanical properties, including *hardness*, shape, and type of fracture;
- Description of chemical properties, including existing and potential chemical weathering;
- Properties of the fine material, including shape and potential for weathering;
- Estimation of index test results; and
- Recommendation for special testing, if necessary.

Acceptance of petrographic analysis for engineering use as indicated in these examples was part of the incentive for the use of the technique as part of the ballast evaluation program at UMass.

BALLAST IDENTIFICATION

Rocks may consist of only one mineral, but they generally consist of an aggregate of mineral types. A mineral is a "naturally occurring, homogeneous solid with a definite, but generally not fixed, chemical composition and an ordered atomic arrangement" (*4*). For example, the minerals calcite and aragonite are both composed of calcium carbonate, but they have different atomic arrangements, which results in the two minerals having different physical properties of *cleavage*, hardness, and specific gravity.

Rocks are generally classified by texture and mineral composition. The texture of a rock is the relationship between the crystals of minerals that form the rock. A description of a rock's texture generally includes grain (crystal) size, grain shape, degree of crystallinity (ratio of glass to crystals) and the contact relationships of the grains. The presence of voids or fractures is included in the description of the structure of the rock but is generally not specifically considered when naming or classifying a rock. Two rocks with similar mineral compositions but different textures would have different names. Initially, rocks can be grouped into three main types—igneous, sedimentary, and metamorphic—on the basis of the mode of formation. Each category is further divided into classifications of rocks according to their texture and composition.

Petrographic analysis involves the study of a rock in hand specimen as well as in thin section. Analysis of a material in hand specimens gives an indication of the approximate composition and texture of the rock. Thin-section analysis allows a more precise assessment of the rock's constituents and texture.

A thin section is a representative section of a rock that has been cut, mounted on a glass slide, and ground to the standard thickness of 0.03 mm (0.0012 in.). At this thickness most minerals will transmit light. The thin section can then be examined using a transmitting light, polarizing microscope. The rock is identified in part by its mineral composition, which can be determined from a thin section by crystal form or grain shape, grain size, cleavage, color in plain light, *pleochroism, birefringence,* extinction angle, *refractive indices,* and twinning. Also important in the identification of a rock are bedding, banding, foliation, texture, porosity, and the presence of fossils or fossil fragments and *peloids.* A thin section can also be stained to distinguish the members of the carbonate and feldspar mineral groups.

Fourteen ballast materials were identified through hand-specimen analysis and 12 of these were also analyzed as thin sections. The materials were classified using several classification systems (*5-9*). A summary of the results of the analyses is given in Table 1. The materials examined represent a wide range of rock types, including both intrusive and extrusive igneous rocks, chemical sedimentary rocks, and medium- and high-grade metamorphic rocks. This range provides a good foundation for the evaluation and comparison of performance based on material type.

EVALUATION OF BOX TESTS

Description of Test

The ballast box test was first developed in 1981 at UMass to study the behavior of ballast under simulated field loading conditions (*10*). The ballast box has an advantage over current standard index tests in that it can simultaneously

TABLE 1 SUMMARY OF HAND SAMPLE AND PETROGRAPHIC ANALYSES

Material	Rock Type	Rock Name	Description	Predominant Minerals	Approximate Percentage
Gneiss 3	Metamorphic	Micaceous quartzo-feldspathic gneiss	A fine-grained, *inequigranular* gneiss with *crystalloblastic* and *lepidoblastic* textures and fair to good foliation	Quartz Feldspar Mica	40 45 10
Granite	Intrusive igneous	Granite	A medium-grained, *phaneritic, holocrystalline, inequigranular* granite; the sample was extensively weathered, with sericite occurring as an alteration product of feldspar and no original *mafic* minerals observed	Quartz Sericite Chlorite Feldspar	35 30 25 10
		Quartz monzonite	A medium-grained, holocrystalline, inequigranular rock with *subhedral* grains; some plagioclase feldspar grains with euhedral inclusions of quartz or feldspar	Feldspar Biotite Amphibole Quartz	45 25 15 15
		Granite	A medium-grained, *equigranular,* holocrystalline rock with subhedral grains; the feldspar frequently had euhedral inclusions and sericite occurred as an alteration product of feldspar	Quartz Feldspar Sericite	45 40 12
Gneiss 2	Metamorphic	Quartzo-feldspathic gneiss	A medium-grained, inequigranular gneiss with subhedral grains, crystalloblastic texture and fair foliation	Quartz Feldspar Biotite Pyroxene	40 30 15 10
Monzonite	Intrusive igneous	Monzonite	A holocrystalline, medium- to coarse-grained rock with subhedral grains and some alteration of feldspar to sericite and clay	Feldspar Biotite Magnetite	95 3 2
Quartzite 2	Metamorphic	Quartzite	A fine- to medium-grained rock composed of sutured quartz grains with rims of hematite and interstitial muscovite	Quartz Muscovite Hematite	90 8 2
Dolomite	Chemical sedimentary	Crystalline dolomite	A compact, fine- to medium-grained rock composed of interlocking crystals with low porosity	Dolomite Calcite	95 5
Micrite	Chemical sedimentary	Detrital micrite	Very fine-grained quartz in a *matrix* of ferroan *micrite*	Calcite Quartz	80 20
Carbonate	Chemical sedimentary	*Sparite*	A medium- to coarse-grained rock composed of interlocking sparry calcite crystals	Calcite	100
		Dolomitic micrite	A very fine-grained rock composed of *cryptocrystalline* dolomite with a vein of intrusive dolomite and calcite	Dolomite Calcite	85 15
		Crystalline dolomite	A medium-grained rock composed of interlocking crystals of dolomite	Dolomite Calcite	95 5
Gneiss 1	Metamorphic	Quartzo-feldspathic biotite gneiss	A medium- to coarse-grained inequigranular gneiss with crystalloblastic and lepidoblastic texture and fair to strong foliation	Biotite Feldspar Quartz Hornblende	35 25 25 15
Quartzite 1	Metamorphic	Quartzite or quartz gneiss	A fine-grained rock with a *groundmass* of sutured and interlocking quartz, with larger crystals of quartz and interstitial muscovite	Quartz Muscovite	85 15
Slag	Artificially produced	Slag	Particle variation from solid and glassy to very vesicular		

TABLE 1 *continued*

Material	Rock Type	Rock Name	Description	Predominant Minerals	Approximate Percentage
Limestone 2	Chemical sedimentary	Dolomitic fossiliferous microsparudite	A fine-grained matrix of microsparry calcite and dolomite; fossiliferous, with original material and large molds filled with sparite	Calcite Dolomite	90 10
Limestone 1	Chemical sedimentary	Bio micrudite	A very fine-grained rock with a matrix of micrite and clay-sized material (unidentified); the rock is fossiliferous, with original material and large molds filled with sparite	Calcite	80
Basalt	Extrusive igneous	Basalt	A very fine-grained (*aphanitic-phaneritic*) rock composed of phenocrysts of feldspar in a groundmass of mafic minerals; individual particles range from highly to slightly vesicular, with a small (relative) amount of nonvesicular (solid) particles; many of the particles are slightly weathered and coated with clay	Feldspar (phenocrysts) Mafic minerals in groundmass	

consider the effect of such variables as material size and gradation, material type, wheel load magnitude, number of cycles of load (i.e., traffic), application of maintenance cycles, and type of tie on the settlement and amount of degradation of a ballast, thereby better simulating field conditions. The ballast index tests can only consider the effects of rock type under one set of test conditions.

Briefly, the box represents a section of the track structure that includes a section of a tie directly beneath a rail seat and a portion of the crib on either side of the tie with a ballast depth of 12 in. or 305 mm (Figure 1). To simulate train traffic, a servohydraulic testing machine is used to repeatedly apply vertical load to the tie segment, cycling at 5 Hz between a minimum load of 100 lb (445 N) and the maximum load, which varies depending on the axle load and track conditions. The computer program GEOTRACK (*11*) is used to determine an equivalent wheel load (EWL) to be applied to the test tie segment so that the ballast beneath the segment experiences the same amount of stress as does the track being represented; that is, to simulate a 50-kip (223-kN) wheel load, an equivalent maximum load of 6,000 lb (27 kN) is applied to the tie segment.

To prepare a box test, a ballast specimen of the desired grading is placed in the box in layers, each lightly compacted by rodding. The material in the zone directly beneath the tie segment is dyed so that any breakage and abrasion that occur during the test will be apparent.

For a standard test, settlement readings are taken periodically until completion of the test. At the end of the test the material is carefully removed and inspected to determine ballast degradation. Coarse breakage is defined as a fragment larger than 3/8 in. (9.5 mm) or a particle from which a piece larger than 3/8 in. has been broken. Fine breakage is any material smaller than 3/8 in. that has been generated during the test through breakage or abrasion, or both. Breakage in each of these categories is given as a percentage of the original sample weight.

36-Kip EWL Tests

Table 2 gives the relative ranking of five ballast materials according to the amount of breakage (*12*) for a 36-kip (160-kN) EWL. In each case, 500,000 cycles of load were applied in a standard test and the gradation used was American Railway Engineering Association (AREA) 4.

Coarse Breakage

In general, in the category of coarse breakage, the relative behavior of these five ballast materials in the ballast box tests is what could be expected on the basis of the data obtained from the petrographic and hand-sample examinations. The metamorphic Quartzite 1, composed essentially of quartz and without inherent planes of weakness, proved to be the most resistant to coarse breakage (Table 2). The medium-grained, foliated Gneiss 1 had a moderately low amount of breakage as did the medium-grained, softer dolomite. This metamorphic gneiss had an amount of breakage similar to that of the dolomite because of inherent planes of weakness in the gneiss due to the grain size, mineral composition, and foliation (i.e., the presence of minerals such as mica and feldspar that have one or more planes of cleavage). The glassy slag had a moderate amount of coarse breakage; breakage was a function of the vesicularity of the particles comprising

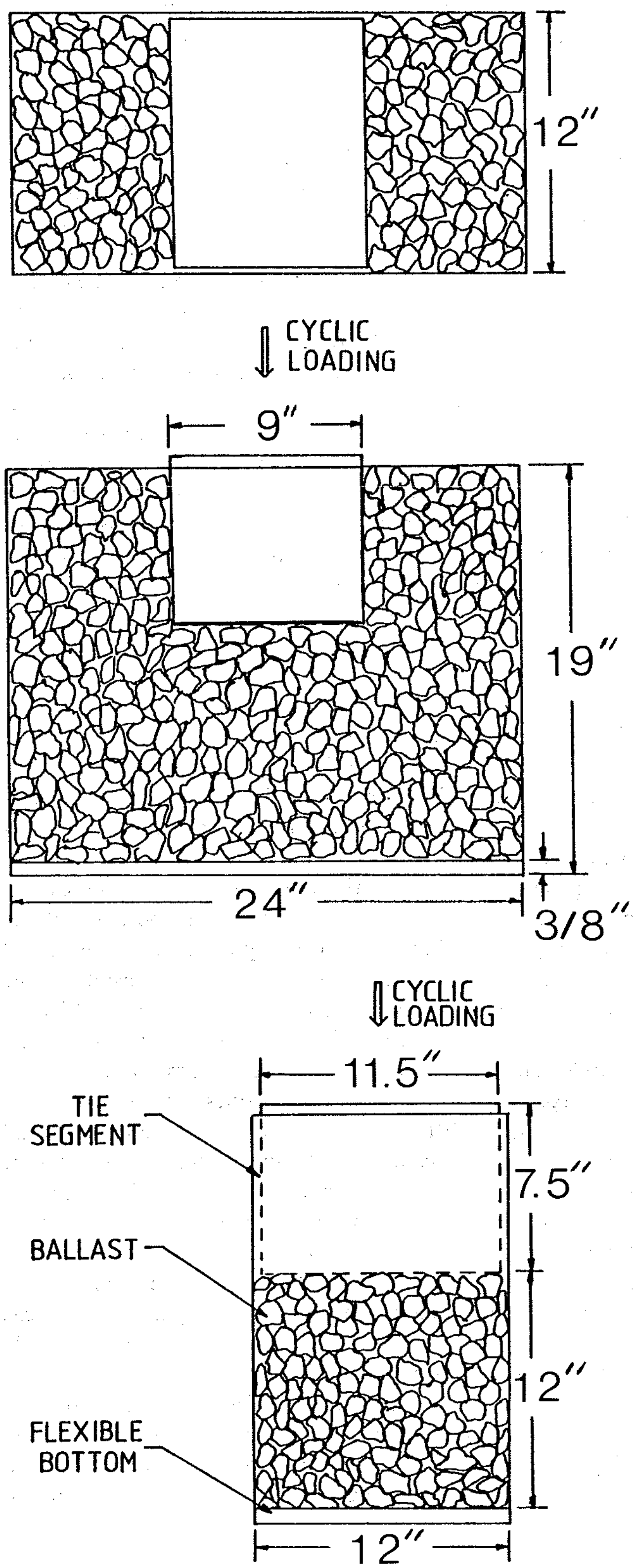

FIGURE 1 Ballast performance simulator.

the test sample. The carbonate material had the greatest amount of breakage. Three rock types, all carbonates, that are soft rocks expected to break easily, were identified in this sample.

TABLE 2 RANKING OF THE BALLAST BOX TEST BREAKAGE FOR 36-KIP EWL

Rank[a]	Breakage >3/8 in. (%)		Breakage <3/8 in. (%)	
	Material	Value	Material	Value
1	Quartzite 1	0.3	Quartzite 1	0.2
2	Gneiss 1	1.3	Gneiss 1	0.2
3	Dolomite 1	1.6	Slag	0.3
4	Slag	2.3	Dolomite 1	0.4
5	Carbonate	4.4	Carbonate	0.7

Note: 36 kips = 160 kN; 3/8 in. = 9.5 mm.
[a] 1 = lowest breakage; 5 = highest breakage.

Fine Breakage

When a sample is prepared for the ballast box test, all material passing the 3/8-in. (9.5-mm) sieve is removed. Therefore any material finer than 3/8 in. present in the sample after testing has been generated through breakage and abrasion of the aggregate particles. The amount of breakage and abrasion that will result from a test is a function of particle shape, surface roughness, and size and gradation, as well as material type.

In general, the amount of finer material generated was as would be expected given the properties of the materials. The trend is similar to that of coarse breakage. The two metamorphic materials, the Gneiss 1 and the Quartzite 1, were the most resistant to abrasion and produced the least amount of finer material, a function of the composition and texture of the rocks. The dolomite had a moderate amount of fine breakage because the rock is basically medium grained and composed of a soft mineral, dolomite, that causes the rock to be more easily abraded at particle contacts, which are areas of stress concentration during loading. The slag also had a moderate amount of fine breakage but less than the dolomite because the slag is a harder material. The amount of finer slag material generated by a given test depended on the ratio of vesicular to glassy particles, the sizes of these particles, and their distribution within the sample. The carbonate material, which was the softest material, produced the greatest amount of finer material; the behavior of the material, and the amount of finer material generated, depended on the rock type or types present in the sample.

50-Kip EWL Tests

The box tests run using a 50-kip (223-kN) EWL are not easily grouped because a consistent gradation was not used in this series of tests. The variation in gradations complicates evaluation of degradation results based on material type. However, two groups with common conditions are (a) Group A with 500,000 test cycles but gradations ranging from AREA 4 to 24 (*13, 14*) and (b) Group B with an AREA 3 modified gradation for either 1 or 2 million cycles (*14, 15*). The results of the 1 and 2 million cycle tests will be considered together on the assumption that most breakage occurs before

500,000 cycles. The results and ranking of these tests are given in Table 3.

TABLE 3 RANKING OF THE BALLAST BOX TEST BREAKAGE FOR 50-KIP EWL

Rank[a]	Breakage >3/8 in. (%)		Breakage <3/8 in. (%)	
	Material	Value	Material	Value
N = 500,000 Cycles				
1	Quartzite 2	0.4	Gneiss 2	0.08
2	Granite	2.2	Quartzite 2	0.09
3	Gneiss 2	2.9	Granite	0.09
4	Monzonite	3.0	Monzonite	0.2
5	Gneiss 3	4.0	Gneiss 3	0.4
6	Basalt	16.1	Basalt	0.8
N = 1 and 2 Million Cycles				
1	Limestone 1	15.0[b]	Limestone 1	0.6[b]
2	Basalt	16.5	Limestone 2	0.6[b]
3	Limestone 2	19.3[b]	Basalt	0.9

Note: 50 kip = 223 kN; 3/8 in. = 9.5 mm.
[a] 1 = lowest breakage, 5 = highest breakage.
[b] Average value of 1 and 2 million cycle tests.

Group A

Coarse Breakage With the exception of Quartzite 2 and the basalt, the coarse breakage trends of the ballasts in this group generally were not as expected on the basis of the petrographic analyses (Table 1) and the gradations of the materials. The Quartzite 2, similar to the Quartzite 1 material, had the least amount of breakage, and the vesicular basalt had the greatest, as expected. The basalt had a high breakage value because of the extreme vesicularity of many of the particles, which results in a rock that is easily broken. However, the material had a smaller amount of coarse breakage than was originally expected. This may be because at the particle contacts a very vesicular rock easily powders and fractures, which would reduce the amount of coarse breakage.

A fair amount of breakage was expected for the Gneiss 2 and Gneiss 3, which are fine-grained, weakly foliated metamorphic gneisses, and a greater amount of breakage was expected from the coarser-grained (intrusive) igneous rocks (i.e., the granite and monzonite). The Gneiss 3 was also tested at the finest grading, AREA 4, again suggesting low values of breakage.

The differences between predicted and actual performance of this group of materials may be due to a combination of differences in gradation and shape. Gneisses 2 and 3, which are similar rocks, showed the most deviation from expected performance. Gneiss 3, which had the greatest breakage of the group (4.0 percent), with the exception of the basalt (16.1 percent), was reported to be the flakiest (*13*). The Gneiss 2 had the coarsest gradation (AREA 24), was the most equidimensional sample, and had a moderate amount of breakage. The remaining materials, granite and monzonite, had low to moderate values. Each was tested at gradations that fell between the specified limits of AREA 24 and 4; no information on shape was available for either.

Fine Breakage With the exception of the Gneiss 3, the performance of the materials in this category was generally as expected on the basis of the determination of rock type. The finer-grained metamorphic rocks (Gneiss 2 and Quartzite 2) showed less fine breakage than the coarser-grained (intrusive) igneous rocks (granite and monzonite) (Table 3). The Gneiss 3 is ranked fifth with 0.4 percent, twice the amount of fine material generated by the fourth-ranked material. The vesicular basalt had the greatest fine breakage with 0.8 percent for the reasons discussed in the previous section. This trend is consistent with the results for coarse breakage, where the basalt showed significantly more degradation than the other materials and the Gneiss 3 had more breakage than expected. The reason for this trend in behavior of the Gneiss 3 is not clear; particle shape and gradation variations complicate the analysis of performance with respect to material type.

Group B

The basalt, Limestone 1, and Limestone 2 were tested in a standard box test at an AREA 3 modified gradation with a 50-kip (223-kN) EWL for 1 or 2 million cycles per test. Table 3 includes a ranking of these materials for each category of breakage.

In general, the comparative breakage behavior of the three ballasts in this group was as expected on the basis of the petrographic and hand-sample analyses of the materials: all three materials had high breakage values. The basalt had the greatest amount of fine breakage, which is explained by the highly vesicular nature of the particles comprising the test sample. The limestone materials had the same values for fine breakage. They are both soft limestones, although they are texturally quite different rocks. The Limestone 1 ballast had the least coarse breakage of the group because of the very fine-grained matrix of micrite and "mud." The coarser-grained Limestone 2 had the most coarse breakage, which is a function of its texture and composition. The Limestone 1 material had less coarse breakage than the Limestone 2 material because it has a fine-grained, muddy matrix, whereas the matrix of Limestone 2 is coarser, composed of slightly altered calcite and dolomite, with many partly filled voids and fractures. The larger crystal size of the Limestone 2 matrix suggests that the cleavage planes of the crystals will play a greater role in fracture initiation and propagation, and the open voids will be regions of stress concentration and fracturing, resulting in a rock that fractures more readily when used as a ballast.

EVALUATION OF ABRASION TESTS

Description of Test

Because a ballast material will degrade through both breakage

and wear, it is desirable to be able to characterize a material's resistance to these modes of degradation. Currently, three tests are used by various railroads for this purpose. These are the Deval, or British Standard wet attrition, test; the Los Angeles abrasion (LAA) test; and the mill abrasion (MA) test. The latter two tests have been incorporated into the UMass ballast program.

In brief, the LAA test consists of tumbling 10 kg (22 lb) of material using one of three gradings (ASTM C535) with 10 to 12 steel balls weighing a total of 5 kg (11 lb) in a drum 28 in. (711 mm) in diameter for 1,000 revolutions at 33 rpm. The material is removed and the sample is washed on a No. 12 sieve. The LAA-value is the amount of material passing the No. 12 sieve generated during the test, called the loss ratio, as a percentage of the original sample weight.

The MA test involves revolving 3 kg (6.6 lb) of a specified gradation of material about the longitudinal axis of a ceramic jar 9 in. (229 mm) in diameter containing water for 10,000 revolutions at 34 rpm. The mill abrasion value is the amount of material finer than the No. 200 sieve generated during the test, given as a percentage of the original sample weight.

The Deval test (*16*) had originally been used in England for evaluating highway materials. The test was standardized in 1951 and adopted for use by the railroad industry. The Deval wet attrition test is similar to the MA test. It involves revolving 5 kg (11 lb) of a specified gradation of material with 5 kg of water in a cylinder 7 7/8 in. (200 mm) in diameter inclined at 30 degrees to the axis of rotation for 10,000 revolutions at 30 to 33 rpm. The wet attrition value is reported as the amount of material less than the British Standard No. 7 sieve generated, as a percentage of the original sample weight.

Since its adoption as a standard test, British Railway has conducted an investigation of the effect of wet versus dry conditions, particle gradation, particle condition, and presence of slurry on the results of the Deval test. The results show that

1. The coarser the grading, the greater the amount of abrasion.
2. Abrasion without water is less than with water.
3. Previously worn particles had much less attrition than freshly crushed particles.
4. The use of a slurry of fines in water increased the amount of abrasion by only a small amount. This is in contrast with field experience in which significant slurry abrasion has been observed, possibly because of the high velocity of liquid movement in the field, which is not present in the Deval test.

Similar results have been found at UMass using the MA apparatus (*14*).

From studies such as these it is clear that the test conditions must be standardized for comparisons of the effects of rock composition on abrasion resistance. However, correlation with field performance is more complicated because such factors as particle gradation, presence of water, and initial condition of particles are not constant in the field.

Los Angeles Abrasion Tests

The results of the LAA tests for every material are given in Table 4, ranked from 1 to 14 (1 = lowest loss); these data are also shown graphically in Figure 2. The LAA-values were provided by the suppliers of the ballast materials. It is not known whether the values are based on the same test procedures, so some inconsistency that will complicate the comparisons may exist among materials.

A material's tendency to fracture or abrade during an abrasion test is a function of material type, particle shape, and gradation. In the LAA test, gradation is fixed; therefore the results will reflect material type and particle shape. No information is available on the shapes or the representativeness of the specimens tested because the LAA-values were provided by the suppliers. Thus the LAA results will be discussed primarily with respect to material type as determined from petrographic and hand-sample analyses, assuming that they are representative of the tested materials.

TABLE 4 RANKING OF ABRASION TEST RESULTS

Material	MA		LAA	
	Rank[a]	Value (%)	Rank[a]	Value (%)
Gneiss 3	2	2.0	4	23
Granite	6	5.6	1	17
Gneiss 2	5	5.4	6	25
Monzonite	3	2.3	3	21
Quartzite 2	1	1.9	2	20
Limestone 2	11	11.4	8	33
Limestone 1	9	7.0	7	27
Basalt	4	4.0	11	48
Gneiss 1	-	-	4	23
Dolomite	8	6.8	5	24
Slag	7	6.5	9	35
Micrite	-	-	6	25
Quartzite	-	-	1	17
Carbonate	10	10.1	10	36

[a] 1 = lowest loss (%).

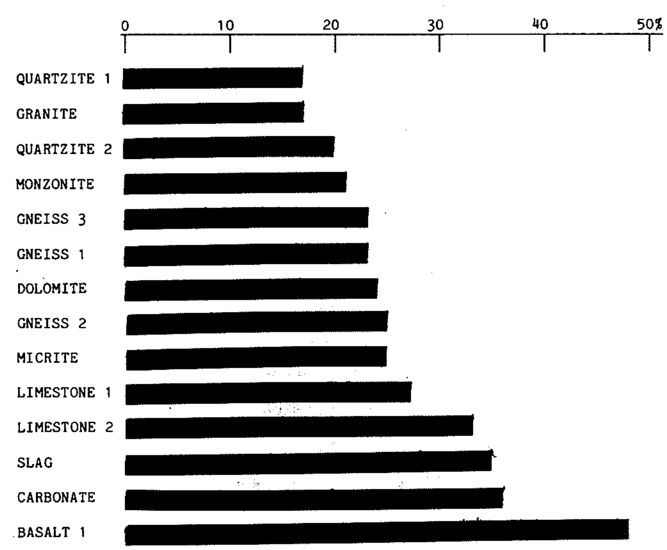

FIGURE 2 Los Angeles abrasion results for various ballast materials.

With some exceptions, the LAA results presented in Table 4 are generally what would be expected. The exceptions are the granite, the monzonite, and the dolomite material.

The granite and monzonite were found to be medium- to coarse-grained ((intrusive) igneous rocks composed predominantly of minerals that have at least one plane of cleavage (Table 1). The granite was found to have at least two rock types (both igneous); a complete identification of the rock types and their abundance in the sample has not been achieved. However, a higher loss was expected. The monzonite was a homogeneous sample of a medium- to coarse-grained monzonite. Because of the texture and composition of the rock (large grains of minerals with two cleavage planes), a higher loss was expected.

The dolomite had a lower loss than would be expected for a soft carbonate rock. This material, however, was found to be a compact rock composed of interlocking fine- to medium-sized grains of dolomite, which is a moderately hard mineral. Therefore the reported value may not be misleading.

The remaining materials have reasonable loss values and follow an expected trend. The two quartzites have low values, the three metamorphic gneisses have moderate losses, the four relatively soft carbonates (micrite, carbonate, Limestone 1 and Limestone 2) have moderate to fairly high losses, and the vesicular materials (slag and basalt) have fairly high to very high loss values (Table 4).

Mill Abrasion Tests

Available standard MA test results are also given in Table 4 and shown graphically in Figure 3 (*12-15*). Because of material limitations, tests could not be conducted using the Gneiss 1, micrite, and Quartzite 1 materials. As with the LAA tests, the results will reflect the rock type and particle shape of the test samples. With the exception of the Gneiss 2, the MA-values are what would be expected on the sole basis of material type.

The metamorphic Quartzite 2 has the lowest value because it is predominantly composed of the hard mineral, quartz. A close second was the Gneiss 3, which contained a large amount of quartz, but also about the same amount of a slightly less hard mineral, feldspar. The monzonite, which was primarily feldspar, was third. The basalt, although it contained feldspar along with other minerals, had more abrasion than the monzonite, probably because of the vesicularity of the particles. Next is the granite with considerable quartz and feldspar. It had a moderate loss but is difficult to evaluate because of the variety of rock types present. The slag had a moderately high loss because of the vesicularity of many of the particles, which created a rougher surface than the glossy particles and hence abraded more readily.

The four carbonate materials had high losses because of the softness of the predominant minerals, calcite and dolomite. The dolomite rock had the lowest loss of the group. The carbonate is a mixture of a variety of rock types and so is hard to evaluate. The two limestones had greater losses than the dolomite. The differences in the two limestones may be a result of their grain fineness.

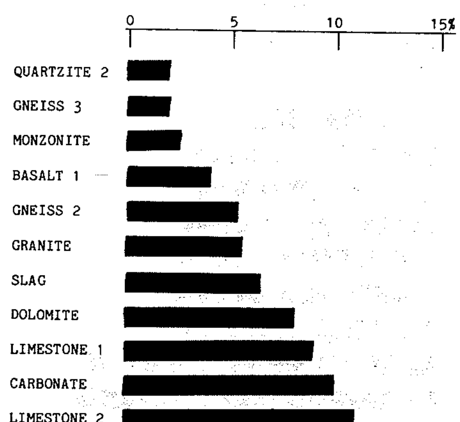

FIGURE 3 Mill abrasion results for various ballast materials.

EVALUATION OF CEMENTING TESTS

Description of Test

Ballast cementing tests (BCT) have been incorporated in the UMass ballast testing program to examine the potential for, and mechanisms of, cementing in ballast fine material, as well as to study the relevance of the test to field performance. An initial study was conducted to determine the effects of grain size, compression state, drying sequence, and curing method on the unconfined compressive strength of a cylindrical briquette 1 in. (25 mm) in diameter by 1 in. high (*12*). The test procedure was standardized on the basis of this study. Results with this test were evaluated according to particle characteristics, including shape and composition. These characteristics were determined from microscopic examination of the fine material as well as hand-sample and petrographic analyses of the source (parent) material.

The first step in the BCT is to crush rock particles and sieve the fines to obtain a sufficient quantity of material of the desired particle size. Then a dough is formed using distilled water, with the water content just above the liquid limit, and left to cure overnight. In the standardized test, the briquette is formed by compressing the dough into a cylindrical steel mold 1 in. (25 mm) in diameter by 1.25 in. (32 mm) long using a pressure of 1,875 psi (12.9 MPa) and a *consolidation* time of 10 min. The briquette is then extruded from the mold, trimmed to a length of 1 in., air dried for 20 hr, oven dried for 4 hr, and then placed in a dessicator until it is to be tested. The test is an unconfined compressive test with a constant strain rate to failure of the briquette. The cementing value, or strength, of the material is the average maximum failure stress for five briquettes.

Fourteen materials were tested with all particles less than the No. 200 (0.075-mm) sieve. The strengths for each are given in Table 5 (*12, 14, 15*). Of this group, the carbonate materials generally had the highest strengths, for the reasons of particle shape and composition discussed previously. The exceptions to this are the Quartzite 1, which had a relatively

high strength, and the carbonate material, which had a relatively low strength (190 psi or 1300 kPa). The higher strength of the Quartzite 1 may result from the properties and shapes of the quartz grains. This is in contrast with the results for the Quartzite 2, which had a very low strength, as expected. The reason for the relatively low strength of the carbonate material is unknown.

Within the high-strength carbonates, the micrite material had the greatest strength, which could be attributed to the presence of detrital quartz grains and the fine-grained nature of the matrix. The dolomite has a high strength due to particle shape (planar surfaces) and, to a lesser extent, composition (i.e., solubility). The strength of the Limestone 1 material could be due to the finer micritic matrix and the presence of the mud particles that may add a bonding factor that would give a higher cement strength for this material than that of Limestone 2, which has no clay. The degree to which bonding will effect the apparent cement strength of the Limestone 1 material will vary with the amount of clay in the sample.

The slag had a moderate strength, which again is most likely a function of the particle shapes. The igneous and metamorphic materials had moderate to low values. Their values were much lower than those of the carbonate materials.

TABLE 5 BALLAST CEMENTING TESTS RESULTS

Material	Strength (psi)
Micrite	1,330
Dolomite	980
Quartzite	650
Limestone 1	560
Limestone 2	490
Slag	320
Carbonate	190
Granite 2	114
Gneiss 3	110
Gneiss 1	62
Monzonite	56
Gneiss 2	53
Basalt	38
Quartzite 2	23

Note: All material passes No. 200 sieve; strength is average for five specimens; kPa = 6.89 × psi.

CONCLUSIONS AND RECOMMENDATIONS

Ballast is a key element in track performance. Ballast behavior in track is influenced by field conditions including

- Axle load magnitudes and number of repetitions,
- Track characteristics,
- Subgrade properties,
- Environmental factors, and
- Condition of track including drainage.

The remaining factors are the following ballast characteristics:

- Rock type and physical characteristics,
- Particle size and shape,
- Gradation, and
- Void ratio.

Ballast behavior will change for the same ballast characteristics if field conditions change. Even the relative ranking of different rock types can vary with field conditions. Petrographic analysis only provides information on rock type and physical characteristics. Furthermore, rock type is not an equally critical factor in all aspects of ballast performance. Thus petrographic analysis alone cannot be expected to provide sufficient information to predict ballast performance. The same is true of the commonly used index tests such as LAA and MA. Nevertheless, petrographic analysis and index tests do have potentially important roles in performance prediction.

Each ballast material used in the UMass research program was evaluated in hand specimen. Also, thin-section examinations were conducted when material availability permitted. The mineral composition, structure, and texture of each material were determined. The information on the physical properties of the materials obtained from these examinations was then used to evaluate the results of the index and ballast box tests performed with the materials, with the goal of determining how these properties correlated with the performance of the material in the tests.

The ballast characterization tests evaluated include the Los Angeles abrasion test, the mill abrasion test, the ballast cementing test, and the ballast box test. In general, petrographic analysis provided a reasonable explanation of the performance of the materials in each of these tests. In cases in which it could not, consideration of material gradation and particle shape could often account for the discrepancies.

The successful application of petrographic analysis to the evaluation of ballast performance in index and ballast box tests suggests that, with further research, the application of the technique can be extended to include an important role in the prediction of a ballast material's field performance. The research should further development of the ballast box to more completely represent field performance and establish (a) which index tests are most suitable, (b) the correlation between the results of the ballast box tests and field performance, (c) the correlation between the results of the appropriate index tests and field performance, (d) the correlation between petrographic analysis and the other tests, and (e) the potential for developing a numerical means of assessing a material's suitability as a ballast using petrographic analysis. The latter could be similar to the method used by the DOH of Ontario or based on a combination of index tests. The prediction of field performance using petrographic techniques would most likely require the evaluation to be made by a petrographer who is familiar with the determined correlations, as well as the physical and environmental conditions such as amount and type (i.e., acidity or alkalinity) of precipitation and temperature patterns.

Field observations are needed to determine ballast characteristics in response to field conditions. The box test would provide a controlled laboratory approach to studying the correlation among index tests, petrographic analysis, and field performance. The index tests are desired for routine

ballast evaluation. Consideration should be given to extending them to represent some of the variables other than material type. Petrographic analysis would provide an efficient and economical means of determining the suitability of a potential quarry or a means of selecting the best material when a variety of materials is being considered. Petrographic analysis can also be used for general evaluations of performance of potential ballast materials, as well as for selection of appropriate index tests, thereby eliminating the need for an entire series of index testing on several materials to determine which is the best material. The evaluation should be made by a petrographer with knowledge of the conditions of the index tests (i.e., what each test is actually testing and what that means with respect to field performance), field conditions, and the effects of gradation and particle shape.

GLOSSARY

Unless otherwise specified, these definitions were taken from Whitten and Brooks (*4*).

Aphanitic: A textural term applied to igneous rocks in which crystals are so fine that individual grains may only be seen under magnification.

Birefringence: Color produced when rays are put out of phase by double refraction. Colors vary with the thickness and orientation of the crystal.

Cleavage: The tendency of a mineral to break along planes of weak bonding. It is described by the number of planes exhibited and the angles at which they meet.

Consolidation: 1. In the geologic sense, the process of conversion of a loose or soft material to a compact, harder material [e.g., sand to sandstone (by cementation)]. 2. In the engineering sense, the gradual reduction in volume of a soil mass resulting from an increase in compressive stress (ASTM D 653-85).

Cryptocrystalline: A textural term used to describe a very fine crystalline aggregate in which crystals are so small as to be indistinguishable except under powerful magnification.

Crystalloblastic: A texture produced by simultaneous recrystallization of several minerals as a result of metamorphic processes.

Equigranular: A textural term applied to a rock in which the constituent grains are all of about the same size.

Foliation: The parallel alignment of platy minerals or mineral banding in rocks, especially metamorphic rocks.

Groundmass: The finer-grained material constituting the main body of a rock, in which larger units are set.

Hardness: A property of minerals that is determined by reference to an empirical scale of standard minerals. Mineral hardness is a "scratch" hardness, as opposed to the engineers' indentation hardness.

Holocrystalline: Those rocks that are entirely crystalline.

Inequigranular: A textural term applied to a rock in which the constituent grains are of markedly different sizes.

Lepidoblastic: A textural term applied to foliations or schistosity (rock cleavage) produced by alignment of planar minerals (e.g., mica).

Mafic: A general term used to describe ferromagnesian minerals.

Matrix: A term that is similar to groundmass, but used for sedimentary rocks.

Micrite: Cryptocrystalline calcite (less than or equal to 0.004 mm). It is used in the description and classification of carbonate rocks.

Microspar: Calcite crystals between 0.004 and 0.015 mm. A term used in the description and classification of carbonate rocks.

Peloid: A pellet of mud of uncertain origin, generally composed of micrite.

Phaneritic: A textural term applied to igneous rocks in which crystals can be separately distinguished by the naked eye.

Pleochroism: This occurs when a crystal shows color under nonpolarized transmitted light. The color changes depending on the orientation of the crystal.

Refractive index: The ratio of the velocity of light in a vacuum to the velocity of light in some other medium.

Sparite: Calcite, with grain size greater than 0.030 mm. A term used in the description and classification of carbonate rocks.

Subhedral: A crystalline solid with imperfectly developed faces.

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