Assessment of embankment fouling from geotechnical testing of railway ballast samples

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ABSTRACT
Railway embankment fouling occurs when fine grained materials fill the voids between the coarse gravel sized particles in the ballast. This process reduces the permeability of the ballast, and causes geotechnical issues within the embankment and misalignment of the rail. This paper presents the results and analysis of a laboratory investigation to determine the source of the fine grained materials that are involved in the railway embankment fouling process. Geotechnical samples were collected on a 16 km stretch of CN track near Joliette, QC from 38 exploration trenches located within the track embankment. The potential source of the fouling material was assessed from the test results. Analysis indicated fouling is likely caused by a combination of abraded ballast material filling the voids, along with minor upwelling of sand sized particles from the underlying sub-ballast. Preliminary mineralogical analyses also indicate similar conclusions.

RÉSUMÉ
Encrassement remblai de chemin de fer se produit lorsque les matériaux à grains fins de remplir les vides entre les particules de la taille de gravier grossier dans le ballast. Ce procédé réduit la perméabilité du ballast, et provoque des problèmes géotechniques dans le remblai et le désalignement du rail. Cet article présente les résultats et l'analyse d'une étude en laboratoire pour déterminer la source des matériaux à grains fins qui sont impliqués dans le processus d'encrassement talus ferroviaire. Échantillons géotechniques ont été recueillies sur un tronçon de 20 mile de voie ferrée du CN, près de Joliette, QC, passant de 38 tranchées d'exploration dans le remblai de la voie. Le matériau de base pour une faute sur piste a été déterminée par comparaison des in-situ et LA abrasée distributions granulométriques, des résultats d'hydromètre et données minéralogiques. L'analyse a indiqué l'encrassement est probablement causée par une combinaison de matériau de lest abrasée remplir les vides, le long avec un upwelling mineur de particules de sable de taille de la base sous-ballast. Préliminaires des analyses minéralogiques indiquent également des conclusions similaires.

1 INTRODUCTION

The fouling of railway ballast occurs when fine grained particles fill the void space between the coarse rock particles (ballast) used to construct the track bed. Rail ballast is generally characterized as rock aggregate between 20 and 65 mm in diameter, placed in a 0.3 m layer underling the track ties and rail to provide stability and free draining conditions. Fouling is defined as fine gravel to clay sized material (4.76 mm to 0.0076 mm) intruding into the coarse ballast to constitute more than 10% of the in place material weight (Selig and Waters, 1994). The source of the fine grained particles can be due to: physical or chemical break down of the materials within the embankment; upwelling of material from the sub-ballast or subgrade layers; or from external sources, such as salt applied to the tracks in winter, wind-blown particles, or material falling from the rail cars (Fig. 1). Examples of fouled track are shown in Figure 2.

To investigate the source and progression of track fouling phenomena, a 6 week field investigation was

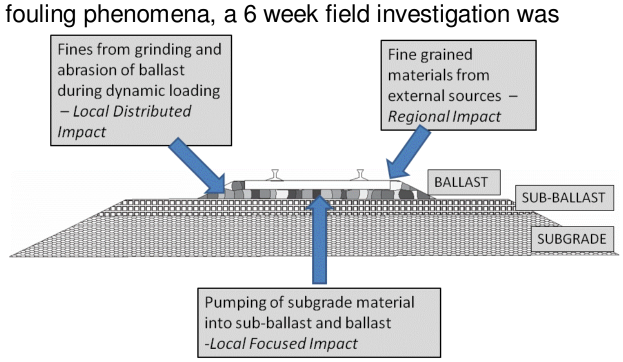


Figure 1: Potential sources of fouling materials within railway embankments.

conducted on a stretch of CN Rail track within the Joliette, QC sub between May, 2010 and June, 2010. This coincided with a ballast undercutting and cleaning operation, providing an excellent opportunity to conduct detailed geotechnical investigations.

Figure 2: Examples of silt/clay plumes developed within the railway embankment, day lighting at the surface of the ballast.

A detailed geotechnical and mineralogical analysis of ballast fouling was conducted on samples collected from trenches excavated during undercutting operations, as described by Bailey et al (2011, this conference). This paper presents the analysis of the laboratory test results, to date.

A preliminary analysis of the potential contribution of different ballast rock types, to the fouling process, has been conducted. X-Ray diffraction analysis of the fine grained portion of the in situ ballast and of the results of the LA abrasion tests on mixtures of ballast have been completed. The assessment of the mineralogical make up of the ballast, sub-ballast and subgrade permits assessment of the possible origin of the fines. The Fouling Index (Selig and Waters, 1994) and the Relative Ballast Fouling Ratio (Indraratna et al, 2011a) were calculated to evaluate the relative durability of the different ballast rock types excavated from the track.

A simple analysis has been developed to estimate the mass transfer that might occur during fouling. By cross-referencing fouling ratios to the depth, lithology, and grain-size distribution of the sample sites, the source and progression of ballast fouling can be estimated.

2 BACKGROUND

2.1 Modes of Ballast Fouling

Three hypotheses to describe ballast fouling were used as the primary criteria for designing the field and laboratory work.

The first hypothesis is that fouling particles originate from the ballast layer itself through in-place abrasion of the ballast layer during dynamic train loading, seasonal freeze-thaw, and/or chemical degradation (Selig and Waters, 1994). These actions are believed to cause the ballast void matrix to gradually fill with abraded fines (Raymond, 1985). This paper defines in-place ballast abrasion as a local distributed impact, since the fouling phenomena is generated in the ballast layer, but is distributed over a relatively large spatial area of the rail embankment.

The second source of fouling is upwelling and intrusion of underlying sub-ballast or subgrade material into the ballast layer (Ionescu, 2004) creating plumes of silt/clay (as shown in Figure 2). These are termed ‘mud boils’ by railway personnel. Upwelling is defined as a locally focused impact, since fouling is caused by distinct conduits of pumped material.

The third potential fouling mode is intrusion from an external source. This may be the result of wind-blown sediment or other forms of particles dropped by passing trains (Tutumluer et al, 2008). This paper defines external intrusion as a regional impact, since the fouling material may be deposited over a regional scale.

2.2 Specified Ballast

The 1996 Canadian National Railway Specification for Crushed Rock Ballast calls for specific criteria to ensure durability and stability of the ballast layer. The grain size distribution range for freshly quarried ballast rock is presented in Figure 3. 95%, or more, of the ballast material should be between the sizes of 20 mm and 65 mm diameter. The ballast rock should also be strong, with minimal structure that may form planes of weakness. Less than 30% of the material should be ‘flat’ with height/length dimensions greater than 1:2. A ballast layer constructed of particles meeting these specifications will have suitable strength to carry train loads, while providing suitable drainage for the track (CN, 1996).

3 FIELD AND LABORATORY INVESTIGATION

3.1 Study Site

The Joliette area was chosen for the research site because undercutting maintenance was scheduled on the sub between Mile 83.5 and 101.3 in the spring of 2010. The study area is located approximately 50 km NE of Montreal, between the towns of Joliette, QC and St. Justin, QC. (Figure 4). The surficial geology of the area directly adjacent to the tracks comprises Champlain Sea clay units of the Ste. Rosalie series, which are characteristic of the St. Lawrence lowlands (Berry and Torrance, 1998) (Figure 5).

The surficial soils in the Joliette study region were formed near the coastal areas of the Champlain Sea, between approximately 12000 BCE and 9000 BCE. The

Joliette region was inundated with sea water as the Late Pleistocene ice sheet retreated north and opened up the St. Lawrence lowlands to the Atlantic Ocean. Sea water was able to flow into the St. Lawrence lowlands due to the isostatic depression caused by the former ice sheet (Davis & Jacobson, 1985). During this time, the St. Rosalie series clays and loams were deposited, along with localized areas of Achigan series sand units.
The section of track studied is underlain by clay (50% of the track length), loam (30%), and sand (20%), based on the surficial soil map (Figure 5).

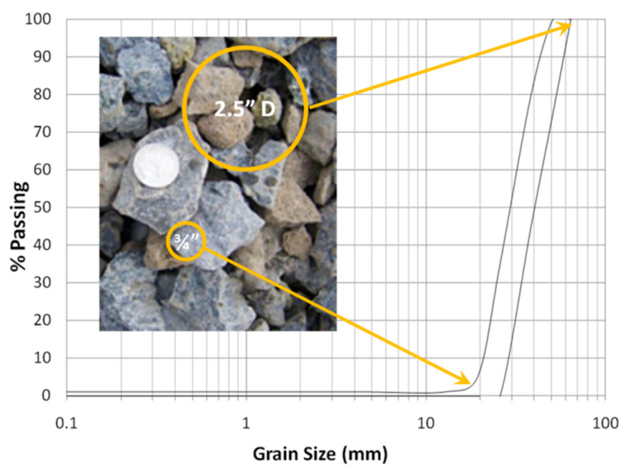


Figure 3: CN Rail Specifications for railway ballast (1996). The yellow circles indicate the range of acceptable ballast particle diameters, relative to the size of the $.25 coin shown in the photograph.

Figure 4: Location of the Joliette sub, where the ballast sampling campaign was conducted.

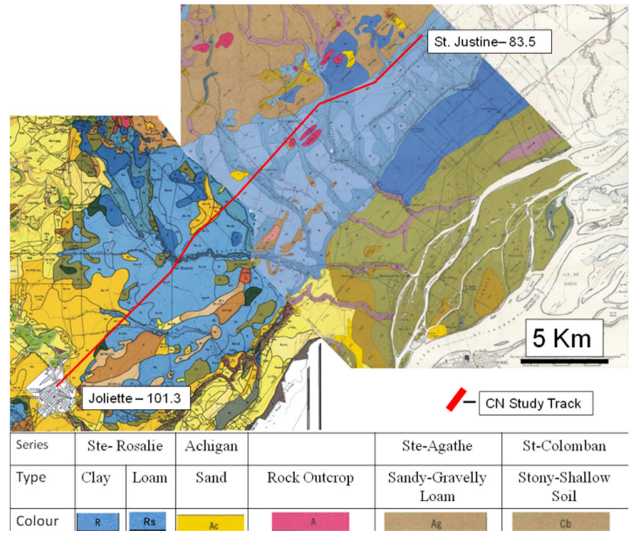


Figure 5: Surficial soils found in the project area on the Joliette sub (from Canadian Department of Agriculture, 1957 Soil Survey of Berthier County – PQ9, and 1961 Soil Survey of Joliette County – PQ28).

3.2 Field Work

The ballast was found to be predominately amygdaloidal basalt, and limestone, along with coarse grained igneous rock and slag. The variety of different rock types found within the ballast was due to historic undercutting operations wherein new ballast is mixed with older, worn ballast. A full reporting of the field and laboratory methods utilized in the project can be found in Bailey et al, 2011 (this conference).

During the field work, the degree of fouling was characterized as either low, moderate, or high. The material was classified as 'low' fouling when a minor intrusion of fine grained material into the ballast layer was observed, but where voids between the rock particles were still visible. 'Moderate' fouling was defined as a condition where fines had fully intruded into the ballast, but when the ballast was displaying non-cohesive behaviour, and was relatively easy to excavate with the trowel. 'Heavy' fouling occurred when fines had intruded through the ballast, right up to the track surface, and the mixture displayed cohesive to strongly cemented behaviour.

3.3 Laboratory Work

Laboratory tests were conducted on the in-situ ballast, fresh ballast, and subgrade samples to measure geotechnical and mineralogical characteristics. The tests are described in detail in Bailey et al (2011, this conference)

Mineralogical testing of the ballast rock types and the fine grained material sampled in situ was important to assess the potential for Type I mechanical and chemical degradation of the ballast, and the resulting fouling agents. With the use of X-Ray diffraction and thin section analysis, both the content and relative abundance of various minerals can be determined for various depths and locations for each trench site assessed.

4 DATA ANALYSIS

The laboratory testing results, discussed in Brennan et al (2011, this conference), permit the following preliminary conclusions to be drawn. As more data becomes available from the analysis, particularly related to the influence of rock type and spatial distribution of the samples within the trenches, these conclusions will be revised and expanded upon.

When all data for samples excavated at depths of up to 15, 30 and 45+ cm below the tie surface were compiled and averaged (Fig. 8, Bailey et al 2011a); approximately 60% of the material still meets the CN specification; less than 4% of the material is of silt or clay size; and the amount of gravel sized particles decreases with depth and the amount of sand sized particles increases with depth.

Table 1 (based on Figure 7 (Bailey et al, 2011a) the representative individual trenches ranked by their subjective amount of fouling witnessed.

Table 1: Ballast grain size analysis for samples with different observed fouling levels, as discussed in Bailey et al (2011, this conference, Figure 7)

	Ballast analysis - data from Figure 7 (Bailey et al, 2011a)	Degree of observed ballast fouling: Lightly, Upper 15 cm	Lightly, Lower 15 cm	Moderately, Upper 15 cm	Moderately, Lower 15 cm	Heavily, Upper 15 cm	Heavily, Lower 15 cm	Hypothesis
Ballast	Meets specification (> 3/4")	75%	70%	58%	70%	62%	55%	If ballast degradation, then <95%
	Fine gravel size	13%	20%	24%	20%	20%	15%	If ballast breakage, then >5%
	Sand size	8%	6%	14%	6%	14%	26%	If ballast abrasion, then >1%
	Silt and clay size			4% to 5%				If ballast weathering, or If mud pumping, then >1%
Sub-ballast	> 3/4"	5%		10%		10%		If mixing of ballast and sub-ballast, then higher value
	Fine gravel size	33%		10%		20%		? Unsure of original grain size distribution
	Sand size	58%		76%		65%		
	Silt and clay size			4 to 5 %				If ballast weathering or If mud pumping, then >1%

In Table 1, it can be seen that as the observed degree of fouling increases, the amount of ballast that meets the specification is reduced. As highlighted with grey shading in Table 1, the lightly fouled samples comprise the largest proportion of particles which continue to meet the ballast specification. The fine gravel sized particles (1” to ¾”) constitute the greatest relative proportion of material in the moderately fouled samples. Sand sized particles constitute the greatest relative proportion of the heavily fouled samples.

4.1 Fine grained materials from external sources

Particles deposited into the track ballast through surface and/or wind-blown sources would be expected to be very fine grained (fine sand, silt, or clay sized). With only 4% or less of each sample falling into this range of particle sizes, it can be concluded that even if this source were active, it would have limited influence on ballast performance.

Mineralogical analysis of the fine grained particles within the ballast, in relation to the mineralogy of the surrounding soils is required to definitively assess this potential impact.

4.2 Pumping of subgrade material into the sub-ballast and ballast

Subgrade intrusion into the ballast layer was studied as a possible method of track fouling. The subgrade beneath the Joliette subdivision track substructure is predominantly Champlain marine clays of the Ste. Rosalie series. The unit is composed of an average of 60% to 70% clay sized particles (≤ 0.0016 mm) by weight, with the balance being of silt and sand sizes (Berry & Torrance, 1998).

During the field work, no examples of focussed subgrade piping were witnessed. In the trench sites characterized as highly fouled, the fine grained material appeared as hard packed sand and silt that was evenly distributed through the ballast layer.

If the underlying clay subgrade were intruding into the ballast layer through the sub-ballast layer, the relative weight of clay and silt sized particles would be much greater than observed. Hydrometer testing of various trench samples indicated that there was an average clay content of 0.21% for 15 cm depth samples, 0.56% from 30 cm depth samples and 0.8% from 45 cm depth samples. Given that the subgrade clays commonly comprise 70% clay particles, the likelihood that clay intruded into any of the sampled locations through subgrade pumping is minimal.

4.2.1 Sub-Ballast Intrusion

Sub-ballast intrusion into the ballast and mixing of the ballast and sub-ballast particles at the layer boundaries were other possible sources of fouling. This would involve either pumping of the sub-ballast into the ballast layer through the action of high pore water pressure or consolidation of the ballast layer into the underlying sub-ballast (Ionescu, 2004). The primary purpose of the sub-ballast is to provide structural stability for the track, free drainage of precipitation, and to prevent the subgrade from piping through the ballast (Raymond,1985).

Sub-ballast at the Joliette site was characterized as medium to coarse sand ranging in colour from grey to dark brown. By weight, subgrade samples contained approximately 70% sand sized particles (0.076 mm to 2 mm), and under 3% clay/silt particles (< 0.076 mm).

During the field investigation, there were no observed instances of focussed sub-ballast upwelling into the overlying ballast layers. Trench photographs also do not demonstrate any explicit examples of sub-ballast material piping into the overriding ballast. However, mixing of the ballast and sub-ballast sand may have occurred.

Comparison between the relative composition of sands by grain size show that in-situ samples of the ballast have very similar sand sized distributions as the sub-ballast (Figure 7). This similarity indicates that there is a possibility that the sand sized portion of the fouling material within the ballast has moved into the ballast from the sub-ballast. It is also important to note that samples from the 45 cm depth show the greatest similarity of sand grain-size distribution between sub-ballast and ballast samples. Therefore, sub-ballast infiltration into the ballast likely has a role in the process of ballast fouling.

Filter criteria can be used to assess the potential for movement of the finer grained sub-ballast material into the overlying ballast. To assess this mechanism of fouling, AREMA (2003) recommends use of filter criteria, based on the size of the grains at 50% and 15% passing, established for water retaining embankments. This criterion indicates that the sub-ballast is at the extreme lower end of acceptable filter material for the ballast, and is therefore on the verge of being small enough to move readily into the voids between the coarse grained ballast.

Past research work has demonstrated that geotextile fabrics installed at ballast and sub-ballast boundaries can help reduce slurry upwelling from either the subgrade or intrusion of sub-ballast layers into the overriding ballast (Indraratna et al, 2011b)

Future work will focus on determining the mineralogy of the sub-ballast sand for comparison with the sand found within the ballast, and in relation to the degree of fouling observed.

4.3 In Place Abrasion

In place abrasion of ballast material through cyclic train loading is one of the most widely reported reasons for ballast fouling (Indraratna et al, 2011b). The dynamic forces induced on the ballast through repeated train loading cause mechanical breakdown of the ballast material over time (Raymond, 1985). To investigate this source of fouling for Joliette Sub ballast, LA abrasion tests were conducted on mixtures of the both fresh and reclaimed ballast

The LA Abrasion test was intended to simulate the abrasion degradation of ballast pieces as they undergo dynamic loading due to the passage of rail traffic. The results from the LA Abrasion test shown in Figure 9 (Bailey et al, 2011a) indicate that the ballast, whether fresh or reclaimed from the undercutting machine, when abraded in the test produces a virtually identical grain sized distribution curve. During the test, the coarser portion of the sample was reduced in size until it just meets the coarse end of the ballast specification. However, 20% of the abraded samples no longer met the ¾” passing specification. The products of the abrasion include fine gravel (8%), sand (8%) and silt to clay (4%) sized particles. These results are closest to the grain size distribution found for the upper 15 cm of the lightly fouled sample in Table 1.

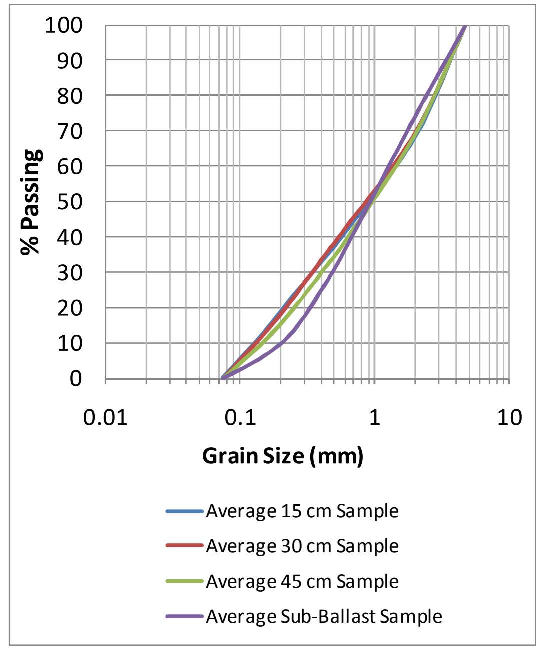


Figure 7. Relative sand grain size distributions for samples taken from: 15 cm, 30 cm, and 45 cm depth below the ties, as compared to the sub-ballast samples.

If an additional 5% of the ballast were to degrade to the fine gravel size in the LA Abrasion test, the grain size distribution would be very similar to near-surface lightly fouled samples. This degradation discrepancy between LA and field data could be explained by seasonal freeze/thaw conditions. Selig and Waters (1994) stated that particles with an abundance of fractured surfaces offer more opportunity for penetration of water and freeze thaw degradation. Angular particles also enable more surface area for freeze-thaw in comparison to round particles. However, verifying this fact is difficult since the sand produced by either freeze-thaw or abrasion cycles would appear the same.

4.3.1 Abrasion dependent on ballast rock type

Mixtures of different rock types were introduced into the LA Abrasion test to assess the relative durability of each of the four rock types found in the samples excavated from the trenches. The LA Abrasion test requires samples containing 5000 g of 1” to 1.5” material and 5000g of 1.5 to 2.5” material. Those trenches containing enough material to generate a sample for the LA abrasion test were sorted by rock type, logged and photographed.

The amount of ballast breakdown can be assessed using a calculated fouling index. Much of the analysis in North America to date has been based on the Fouling Index (FI) proposed by Selig in a number of publications, including Selig and Waters (1994), which is the sum of the percentages of the sample passing the No. 4 (sand) sieve and the No. 200 (silt and clay) sieve. The Relative Ballast Fouling Ratio (RBFR), proposed recently by Indraratna et al (2011a), is based on the ratio of the ballast and fouling portions of the sample, determined as the weight of the material retained on (ballast) and passing (fouling) the 9.5mm (3/8") sieve. The RBFR also considers the specific gravity of the fouling material.

The results of the testing of the different ballast rock types in the LA Abrasion test are summarized in Figure 6, using both the FI and the RBFR. Mixtures of different rock types are plotted in a vertical line, related to the specific fouling index calculated for each individual test. Here it can be seen that the greater the limestone content, the more fouling sized material was formed during abrasion. These results are expected, given that limestone would abrade the most rapidly due to its soft mineral component (calcite – Moh's hardness of 3). LA abrasion tests were run with basalt ballast, as well, however only freshly quarried basalt ballast was available in sufficient quantities for the test. Thus, it wasn't possible to compare the RBFR between 100% limestone and 100% basalt abrasion samples due to their differing pre-testing condition. In comparison, basalt (feldspar, quartz) and slag (quartz) are much harder and therefore are more abrasion resistant materials (Moh's hardness of 6.5 to 7).

While the LA abrasion test doesn't completely simulate the breakdown of the in situ ballast, as discussed above, the test did show that enough fine grained material could be created to cause track fouling, especially with samples composed primarily of limestone. Track regions with greater limestone compositions are likely to exhibit higher relative ballast fouling ratios due to preferential breakdown of the softer limestone ballasts. Further classification of the rock types found in the study samples is required to draw more thorough conclusions.

4.3.2 Grain Migration

The mechanism of fouling, when the ballast degrades by abrasion, is thought to involve the migration of the fine grained products of the abrasion into the underlying ballast void space. This mechanism was investigated using a simple model where ballast sized spheres are reduced in volume.

For example, the reduction of ballast stone by abrasion, from 1.5" diameter to 1" diameter, would result in a 70% reduction in the stone's mass. 70% of the ballast mass would be turned into fine grained material, and only 30% of the remaining sample would be retained on the 1" sieve. Similarly, reduction of 1" diameter material to ¾" material would result in a 42% reduction in the mass of the ballast pieces, leaving 58% of the original ballast retained on the ¾" sieve.

A further assumption is that the ballast degradation by abrasion is originally initiated in the ballast closest to the track surface. As this material is abraded, the ballast is less able to support the dynamic loading, and the deeper parts of the ballast support are engaged in supporting the train loading. As this happens, the deeper pieces of ballast rock are also abraded. Throughout this process, the fine grained particles generated by the abrasion, move down into the voids in the ballast. Once all of the void space is filled with fine grained materials, the fouling material will start to be ejected at the track surface during train passage.

To evaluate this hypothesis, the average in situ mass distribution from the material sampled in Joliette is summarized in Table 2. In this table, the data is compared to the CN specification (1996; as discussed in Bailey et al, 2011a). For example, the maximum amount of fresh ballast allowed, by the specification, to pass the 1" sieve is 35%, meaning that at least 65% of the ballast must be retained on the 1" sieve.

Table 2: Distribution of the ballast mass with depth, as related to CN Rail's (1996) grain size specification.

In situ Mass Distribution (%)		Compared to CN Specification (1996)	
Depth (from top of tie)	1" to 2.5"	% Lost	% Remaining
15 - B	35	46%	54%
30 - B	42	35%	65%
45 - SB	42	35%	65%
CN - min	*65*		
Depth (from top of tie)	¾" to 1"	% Lost	% Remaining
15	30	0%	100%
30	20	33%	67%
45 - SB	18	40%	60%
CN - max	*30*		
Depth (from top of tie)	< ¾"	% Gained	% Remaining
15	35	600%	700%
30	38	660%	760%
45 - SB	40	700%	800%
CN - max	*5*		

The data in Table 2 indicates that the larger ballast pieces are abrading significantly, with at least a 46% loss of ballast sized rock in the upper 15 cm, and at least a 35% loss in the lower sections of ballast. This process generates smaller sized particles which are accumulating in the lower ballast layer.

Some of the fine gravel particles (¾" to 1") seem to be accumulating in the upper 15 cm, as there is no apparent overall loss of this grain size in this section of the track structure. However this size is depleted by up to 40% in the lower sections of the ballast structure.

Finally, the sand sized particles are accumulating throughout the ballast, with the largest gains in mass found in the deepest part of the ballast. As noted previously, some of the sand sized particles in the deeper sections of the ballast may also be moving up into the ballast void space from the sub-ballast layer.

The % of material lost falls within the bounds of the hypothetical abrasion losses discussed above, with a 70% loss for a change in particle size from 1.5" to 1", and a 42% loss for a change in particle size from 1" to ¾". These calculations indicate that abrasion of ballast and transfer of the fine grained particles within the mass is a probable cause of fouling. However, more work is required to refine and verify the abrasion model across varying fouling ratios and rock types.

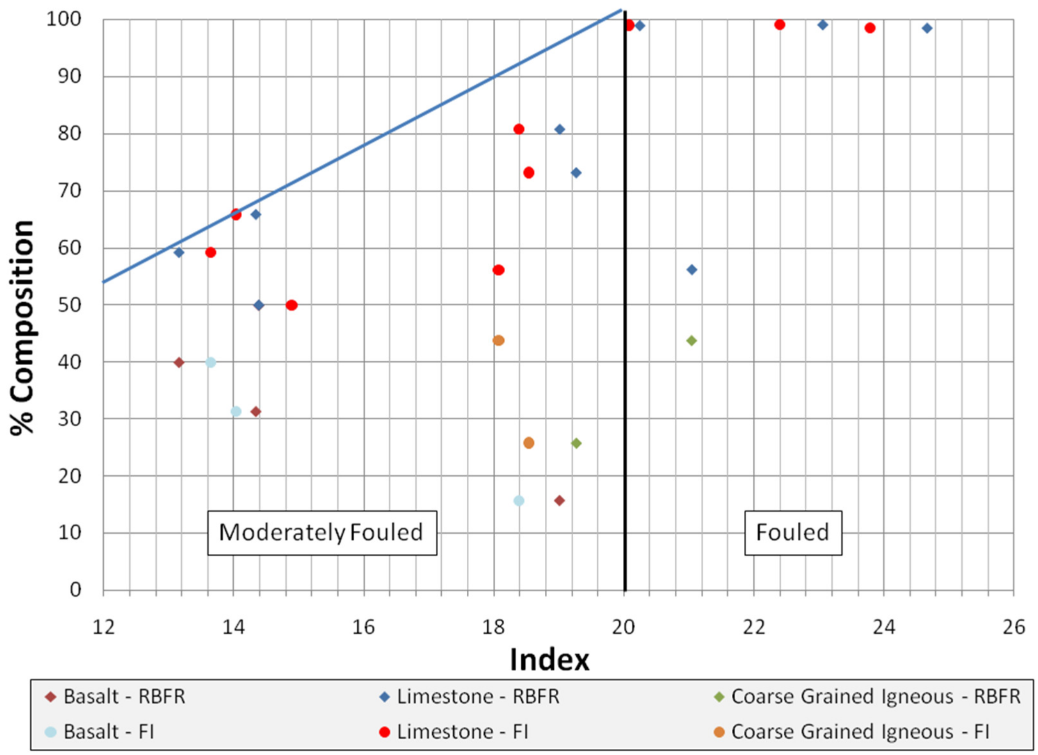


Figure 6: Relative ballast fouling ratio calculated for the results of LA abrasion tests, dependent on the rock types included in the test.

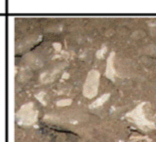
Joliette, Quebec - Sensitive Clay plains					
	Fresh Ballast		**Lightly Fouled**	**Moderately Fouled**	**Heavily Fouled**
Field Descriptions		Abrasion tested	Minor "mud" instrusion into ballast	"Mud" instrusion into ballast, non-cohesive behaviour	Full "mud" intrusion to the ballast surface, cohesive to cemented behaviour
Photograph (10 cm field of view)					
% < 3/4", or below spec	0 to 5%	20%	25 to 30%	30 to 45%	35 to 50%
% sand size, or smaller	0%	about 10%	about 10%	10 to 20%	20 to 30%
% fine grained	0 to 1%	4%	0 to 4% Hydrometer & Atterberg testing required, when > 5%		

Figure 8: Results of grain size distribution analysis for samples categorized by the degree of fouling

5 DISCUSSION

The observations of ballast fouling during field work along with the grain size distributions determined from the laboratory work are summarized in Figure 8 (previous page). The weight percentage of material passing the ¾" sieve within the ballast matrix increases to between 35% and 50%, as track fouling progresses from fresh ballast to highly fouled ballast. From the results presented in this paper, the increase in sand sized particles within the ballast to between 20% and 30% is likely due to abrasion of the in-place ballast by cyclical train loading. This hypothesis is based on analysis of the LA abrasion results and simple abrasion volume loss modeling. In addition, a portion of the sand may also come from intrusion up from the sub-ballast layer, as evidenced by the high degree of similarity between the relative distribution of sand sizes within both the sub-ballast and fouled ballast materials.

6 CONCLUSIONS

The following conclusions can be made about the source and progression of ballast fouling based on the results presented in this paper:

- Ballast fouling through regional intrusion by aerial deposition or precipitation of fines is highly unlikely due to the lack of fine grained particles found within fouled ballast.
- Fouling due to the upwelling of the underlying Champlain sea clay subgrade is highly unlikely due to the lack of laboratory and field evidence for high clay content, or focused pockets of fine material.
- There is a possibility of fouling through the intrusion of sand sized particles from the sub-ballast layer into the overlying ballast layer as evidenced by the similar relative grain size profiles for sand particles in both sections.
- There is a high possibility of track fouling occurring through in-place abrasion based on the amount of potential fines created during LA abrasion tests and mass migration calculations conducted using the grain size distribution data.
- More work is required to assess the rock types contained within the in-situ ballast and sub-ballast samples to evaluate the mineralogical test results.

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REFERENCES

AREMA. 2003. *Manual for Railway Engineering*. American Railway Engineering & Maintenance-of-way Assoc.

Bailey, B., Hutchinson, D.J., Gordon, D., Siemens, G., and Ruel, M. 2011a. Field and laboratory procedures for investigating the fouling process within railway track ballast. *Proc. of 2011 PanAm CGS Geotechnical Conference*. 8 pp.

Berry, R.W., and Torrance, J.K. 1998. Mineralogy, grain-size distribution and geotechnical behaviour of Champlain Clay core samples. Quebec, *The Canadian Mineralogist*, 36: 1625-1636.

CN. 1996. Canadian National Railway Specification for Crushed Rock Ballast. 12-20B. Montreal, QC, Canada.

Davis, R.B. Jacobson, G.L. 1985. Late Glacial and Early Holocene Landscapes in Northern New England and Adjacent Areas of Canada. Quaternary Research, 23: 341-368.

Indraratna, B., Su, L., Rujikiatkamjorn, C. 2011a. A new parameter for classification and evaluation of railway ballast fouling, *Canadian Geotechnical Journal*, 48: 322-326.

Indraratna, B., Salim, W., Rujikiatkamjorn, C. 2011b. Advanced Geotechnology – Ballasted Track, CRC Press, London, UK.

Ionescu, D. 2004. Evaluation of the engineering behavior of railway Ballast. Ph.D *thesis*, *University of Wollongong,* Wollongong, Australia.

Raymond, G.P. 1985. Railroad Ballast Specification and Evaluation – Lecture Notes, *Queen's University,* Kingston, Ontario, Canada.

Raymond, G.P. 1986. Lessons Learned from Geotextiles failures in Railway Rehabilitation Applications, *Queen's University,* Kingston, Ontario, Canada.

Selig, E.T., and Waters, J.M. 1994. *Track Geotechnology and Substructure Management*, Thomas Telford Services Ltd, London.

Tutumluer, E. Dombrow, W., and Huang, H. 2008. Laboratory characterization of coal dust fouled ballast behavior, *Journal of the Transportation Research Board*, 2117: 93-101