Investigation of Ontario's Fine Aggregate Sources for use in Exposed Concrete Pavements

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Abstract

Pavement friction is an integral component in the design process of large volume, high speed roads. Research has shown that the fine aggregate of exposed Portland cement concrete (PCC) pavements is a significant contributor to pavement friction for these types of wearing surfaces. Acid insoluble residue (IR) testing that restricts the carbonate content of fine aggregate is used by many transportation agencies as an indicator of aggregate suitability for pavement frictional performance. Until recently, the Ontario Ministry of Transportation (MTO) restricted the use of manufactured sands for PCC pavements obtained from carbonate bedrock deposits, which underlay a majority of the heavily trafficked portion of the province. Natural sands from surficial deposits had no restriction, meaning these pavements could still contain an undesirable amount of carbonate fine aggregates. In an effort to improve frictional properties of Ontario highways and standardize requirements, MTO recently implemented new IR specifications that apply to all fine aggregates used in concrete pavement surfaces. The new specification also allows suppliers to blend material to meet the insoluble residue targets, which was traditionally not allowed.

Since insoluble residue test data of Ontario fine aggregate sources are not readily available, this project aims to provide representative test data of available natural sands in the context of Ontario and MTO needs. Specifically, the project examines Ontario concrete sand supplier material in relation to the new insoluble residue requirements to show current product availability. Furthermore, the project investigates how production methods affect an aggregate's ability to meet these requirements and correlates various test methods used for assessing durability, silicate rock content, mineral content, and other properties of concrete fine aggregate. The results of this project may be used to support exposed concrete pavement frictional performance in Ontario.

The project has shown that at least **23%** of sources currently producing concrete fine aggregate for the southern Ontario market are capable of successfully meeting a minimum 60% IR_{R75} requirement. An additional **18%** of current suppliers are capable of achieving 50 to 60% IR_{R75} results. These suppliers that fall just short of the 60% IR_{R75} target may benefit from adjustment of their processing operations and/or a minor amount of blending. An IR_{R75} range of 40-50% was achievable for **32%** of the currently producing concrete fine aggregate sources. These suppliers are also within reach of the specification limit and may benefit from the new blending allowance, which will provide many suppliers the opportunity to produce material for future exposed PCC pavement contracts.

Material processing has been shown to have a noticeable impact on the final insoluble residue content. Over half of the sources showed a beneficial impact in relation to insoluble residue targets, with a noticeable beneficial trend for outwash sources. This effect allows some suppliers to increase insoluble residue results by altering their processing techniques. This trend should be investigated further to optimize this advantage.

1. Introduction

The Ontario Ministry of Transportation (MTO) is responsible for developing specifications for materials that help to ensure the safe performance of the provincial highway network. Of particular interest is the contribution of the fine aggregate portion (material passing the 4.75mm sieve) and their effects on the frictional properties of exposed Portland cement concrete (PCC) pavement surfaces. This study examines the composition of fine aggregates from numerous sources within Ontario that are available for concrete manufacture. While PCC pavements are approximately 1.8% of the provincial highway network, these types of pavements are of great importance because they are mainly utilized by MTO for high traffic volume roadways with posted speed limits over 90 km/hr.

MTO recently introduced a change to their specifications that requires fine aggregates (natural sand and manufactured sand) for exposed PCC pavements to meet a minimum of 60% insoluble residue (IR) content. The IR value is determined by using hydrochloric acid to digest carbonate minerals present in a sample. After complete digestion, the remaining mass is made up of acid insoluble content, e.g., quartz, feldspars and other silicate minerals. Other agencies have also applied similar insoluble residue requirements for fine aggregates for use in exposed concrete pavements: Texas (TXDOT) specifies a 60% IR requirement, while several Australian road authorities also have a minimum 60% IR requirement. Previously, Ontario Provincial Specification required a minimum of 50% insoluble residue (IR) content for exposed PCC pavements only if the fine aggregate was manufactured sand made from carbonate bedrock.

Several studies have demonstrated that the mineralogy of the fine aggregate used in a concrete pavement is a critical factor in determining that pavement's frictional performance (Hall et al., 2009). Carbonate rock types are composed predominantly of relatively soft minerals that have a tendency to polish under the influence of traffic resulting in surfaces with reduced frictional properties. On the other hand, silicate minerals are typically harder and more durable and subject to less abrasion and polishing. In general, aggregates that have a higher silicate mineral content lead to better friction.

MTO recognizes that not all fine aggregate surficial deposits of natural sand within the province are able to meet the new requirements without some form of beneficiation. For this reason, MTO specifications also allow materials to be blended with non-carbonate material to achieve the IR requirement. This is a modernization for MTO specifications that have historically disallowed blending of materials for quality purposes.

MTO currently maintains and makes available to contractors, a list of concrete aggregate sources (CASL) for potential use in concrete. Sources wishing to be included on this list are pretested annually for alkali aggregate potential, which in some cases may take up to a year to complete. Since IR testing has not been routinely carried out for this purpose and because there was no previous IR requirement for natural sands, there is limited IR data on surficial deposits within the province. However, in a recent MTO study of historic fine aggregate sources used in concrete pavements on provincial highways (n=30), approximately 38% of the sources were able to meet the new criteria. Since, most of the sources in this historic study have been depleted or are close to their supply limit, an updated picture of Ontario's concrete fine aggregate sources is required. Currently there are approximately 114 different sources of concrete fine aggregate listed on MTO's CASLs within Ontario borders. Twenty seven of these fine aggregate sources are located in the northern part of the province and 87 are located in the south.

To provide an understanding of current aggregate resources and their ability to meet the new IR testing, samples were collected and tested from a subset of CASL fine aggregate sources. Specific questions to be answered by this project include: 1) how many existing sources conform to the requirements?; 2) do production methods affect a fine aggregate's ability to meet IR requirements, and if so, how?; and 3) how do other methods for assessing the durability and siliceous rock and mineral content of the fine aggregate compare with insoluble residue results?

2. Background

Since the late 1960's, major efforts have been made to measure and improve the frictional properties of pavements in Ontario. MTO currently uses a proactive approach to providing an adequate level of wet pavement friction through a selection of skid-resistant aggregates, in conjunction with suitable mix designs for asphalt pavements. Aggregate acceptance for use in high traffic volume asphalt pavements is based on a combination of laboratory testing followed by construction of a pavement test section. Long-term durability of the pavement test section is evaluated, and frictional values are measured using the ASTM brake-force trailer, prior to approval of an aggregate source. Inspection and skid testing continues over the life of the test section, even after aggregate source approval. This practice of aggregate pre-qualification based on laboratory testing and pavement test sections having satisfactory durability and friction has been in place since the early 1980's. Since the early 1990's MTO has required that these sources of skid-resistant aggregate for premium asphalt applications be listed on a Designated Sources for Materials List (DSM). To remain on the DSM an aggregate producer must continue to provide a consistent product of uniform quality and performance characteristics.

A similar program of aggregate prequalification related to frictional properties has not been implemented in Ontario for exposed concrete pavements. Most Portland Cement Concrete (PCC) pavements in Ontario are typically constructed with locally available carbonate aggregates (Rogers et al., 2003). This is a concern from a skid-resistance point of view as carbonates are well known to have a tendency to polish under traffic wear. Several agencies worldwide have addressed this at the concrete mix design stage by requiring a minimum amount of hard, durable, abrasion and polish resistant particles to be incorporated in the fine aggregate portion of concrete mixes.

2.1. Frictional Properties of Pavements

The main components of pavement surface texture that affect frictional properties are macro-texture and micro-texture. Macro-texture is the large-scale texture in the range of 0.5 to 50mm wavelength and 0.1 to 20mm amplitude (Hall et al., 2009), and is a measure of the surface relief of a pavement. Macro-texture is usually achieved by the projection of coarse aggregate in asphaltic surface course mixes or by the finishing method, e.g., tining, for PCC surfaces. Micro-texture is the small-scale texture with a wavelength of less than 0.5mm and amplitude between 1 and 500µm (Hall et al., 2009). In asphalt, good micro-texture is best described as the sandpaper-like feel of the coarse aggregate particle surface. In PCC pavements, microtexture is influenced by the fine aggregate fraction of the mix.

Pavement material properties directly affect the micro-texture and macro-texture of a pavement. For example the projection of coarse aggregate depends on both the mix design and on the wear resistance of the aggregate, whereas micro-texture qualitatively varies from harsh to polished and is dependant primarily on the aggregate petrographic characteristics and traffic intensity (Kennedy et. al., 1990).

In wet conditions, macro-texture provides avenues for surface water drainage which limits bulk water buildup and the potential for hydroplaning. This drainage of bulk water leaves a thin film of water which the micro-texture is able to penetrate to achieve dry contact with the tire. Good micro-texture is important in affecting friction at relatively low vehicle speeds up to 72 km/h (Fowler & Rached, 2012). At higher speeds, macro-texture facilitates the drainage of water, limiting hydroplaning and allowing the adhesive component of friction to be established by the micro-texture.

Wear-resistance of the aggregate is determined by the hardness of constituent mineral grains that compose a rock and the strength of the bond between the grains (Rogers et al, 2003). Aggregates composed of well-bonded silicate minerals have a much greater hardness and resistance to abrasion as compared with those composed of carbonate minerals. Polishing-resistant aggregates are those that are able to retain a relatively harsh sandpaper-like texture under wear or that behave in such a manner as to continually regenerate this texture, e.g., dolomitic sandstone.

Ensuring that the selected aggregates have the appropriate physical, chemical, and mechanical properties is the most important factor in achieving long lasting pavement friction (Hall et al., 2009). MTO strictly regulates the type and composition of surfacing material for asphaltic pavements, where the choice of mix design and material type(s) depends on variables such as traffic volume and geographic location.

2.2. Concrete Pavements

For asphalt surface, micro-texture is provided by the exposed coarse aggregates in the mix. However, in PCC pavements, the coarse aggregates are not exposed so the micro-texture must be provided by some other means. Several studies have demonstrated that the mineralogy of the fine aggregate used in a concrete pavement is a critical factor in determining that pavement's frictional performance (Hall et al., 2009) since the exposed surface of a PCC pavement is primarily made up of cement paste and fine aggregate, while the coarse aggregate typically lies beneath the surface. In general, sands with higher silicate mineral contents lead to better friction. Coarse aggregate is critical only when an exposed coarse aggregate finish is utilized; however this type of finishing method is not commonly used in Ontario. Other factors that also play a role in the skid resistance properties of PCC pavements include aggregate gradation, water-cement ratio, air content, curing method, and the surface finishing method (Lee et al, 2003).

MTO uses several test methods to assess and predict the frictional properties of coarse aggregates used in premium asphalt mixes. The Aggregate Abrasion Value (AAV) is a test that evaluates an aggregate's resistance to abrasion and macro-texture retention, while the Polished Stone Value (PSV) test is used to evaluate micro-texture and polishing resistance. However, the PSV test does not transfer well when assessing the micro-texture of fine aggregate in PCC pavements. Indeed, there are no widely accepted test methods to assess polishing characteristics of a fine aggregate at the present time. Instead, the acid insoluble residue test (MTO LS-613, ASTM D3042) is used to evaluate the carbonate content of a fine aggregate material, and theoretically, the amount of soft minerals present. To date, the IR test has been reported to best relate to friction in concrete pavements and is widely used and accepted (Hall et al., 2009). Typically, minimum IR values used by transportation authorities for good frictional performance in PCC pavements ranges from 50 to 70 percent (Hall et al., 2009).

3. Materials and Testing

3.1. Sampling

Samples of fine aggregate from 44 different commercial sources within Ontario were collected for this project over a period from September to December 2015.

Aggregate sources were selected for several reasons including;

- Proximity to PPC pavement markets (GTHA, Ottawa, Windsor-Essex Corridor).
- Size and capacity of aggregate production
- Type of aggregate products available
- Geological diversity
- Geographic distribution
- Input from MTO Regional Aggregate Resource Information Officers

A summary of sources sampled by region is provided in Table 1, and source locations are shown in Figure 1. The focus of this project was on southern Ontario where most active sources of concrete fine aggregate are located because of proximity to market. Sources were chosen with consideration for good representation of Ontario's geographic and geologic diversity. Almost 50% representation of all southern Ontario CASL fine aggregate sources was achieved during this sampling program (41/87).

Table 1. Fine Aggregate Sources Sampled for this Project by Geographic Area and within MTO Region.

MTO Region	Number of Sources
Northwest Region	0
Northeast Region	3
West Region	18
Central Region	10
East Region	13
Total	**44**

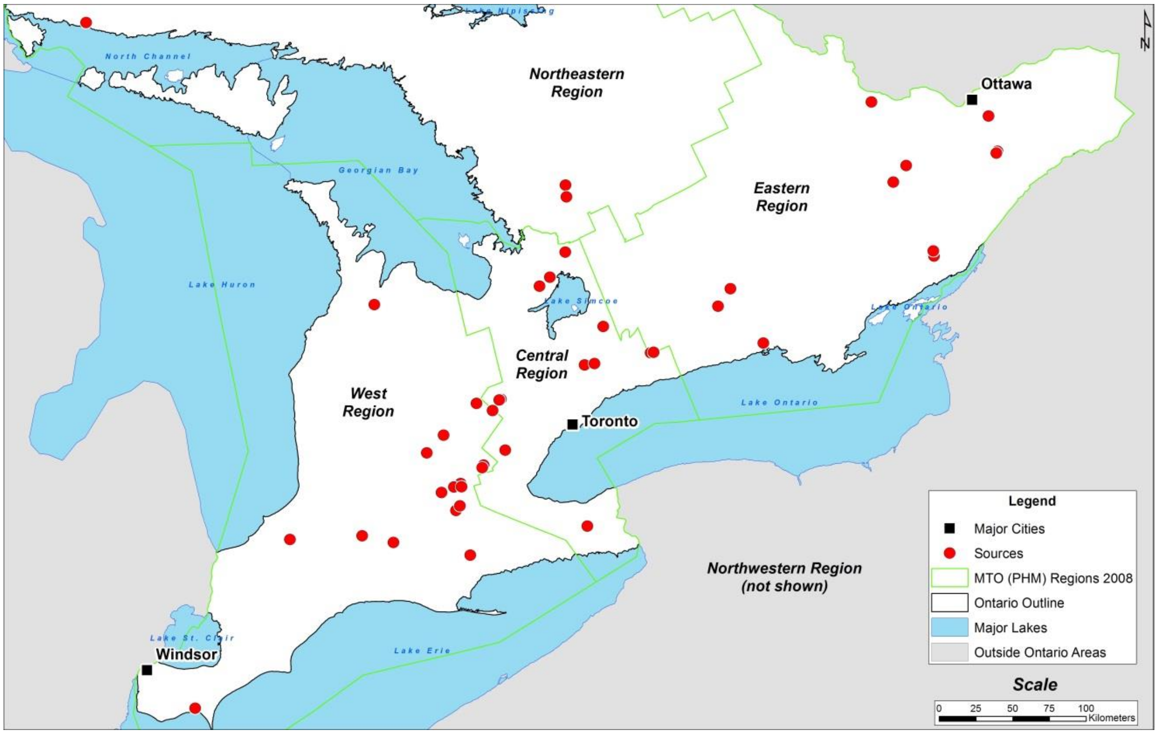

Figure 1: Project Study Map Area – Aggregate Source Locations Sampled, N=44. Note that only southern Ontario and a portion of northeast Ontario are shown on this map. No sources were collected north of the area shown on this map.

3.2. Material Types

Collected materials generally fell into two categories: processed and unprocessed. Processed materials consisted almost entirely of the for-market concrete sand sold at the source by the aggregate producer. These materials typically would have undergone one or more of the following processes: washing, classifying, crushing or the addition of crushed screenings. These samples were usually taken from product stockpiles of concrete sand (majority of samples). Other material types sampled under the processed category (A samples) are indicated in Table 2.

Unprocessed materials (B samples) were sampled from a variety of products detailed in Table 3. The intent of the unprocessed sample was to get a material as close in composition as possible to the “raw feed” entering the processing stream at the aggregate source. Unprocessed samples were available and collected from 39 of the 44 sources sampled (Table 2). The unprocessed materials were compared to the finished concrete sand product to see how production methods can affect the composition and properties of the final material.

Table 2. Summary of Samples and Material Types Collected

Sample Category	Material Source Type	Number of Samples
Group A Samples (Processed)	**Finished concrete sand product***	44
	Washed sand	
	Block sand	
	Screened road base (OPSS 1010, Granular A)	
Group B Samples (Unprocessed)	Sampled directly from the pit face	39
	Pit run sand	
	Dry screened sand	
	Winter sand	
	Road subbase material (OPSS 1010, Granular B)	
Total		**83**

**This accounted for the vast majority of "A" samples collected.*

3.3. Test Methods

All samples were oven-dried and split over the 4.75mm sieve to remove coarse aggregate prior to testing. A summary of the different test methods both processed and unprocessed samples were subjected to for this study are included in Table 3.

Table 3. Summary of test methods used in this study.

MTO Test Method	Description
LS-600	Preparation of Aggregate Samples
LS-602	Sieve Analysis
LS-613	Insoluble Residue
LS-616	Fine Aggregate Petrographic Analysis
LS-619	Fine Aggregate Micro-deval Abrasion

4. Results and Discussion

Test data was divided into 3 groups based on the types of samples collected and proximity to PCC pavement markets (Table 4).

Table 4. Sample groupings used for analysis

Group	Description	Quantity
A	Includes only processed samples of "finished product", typically the for market concrete sand sold by the source.	44
A^1	Subset of the Group A samples. Includes current and potential future suppliers of sand for PCC pavement.	17
B	Includes only the unprocessed samples available at 39 of the 44 sources sampled to represent the raw feed.	39

Group A^1 results include sources identified by MTO's Aggregates Resources staff as probable suppliers of aggregates in proximity to potential future PCC pavement projects. Seventeen sources were identified as likely suppliers based on two criteria. The first identified sources previously used as a fine aggregate in concrete pavement applications. The second criterion although subjective, included sources not previously utilized as a fine aggregate in a concrete pavement application, but had large high volume permanent processing plants located in proximity to where concrete pavements could be utilized, i.e., existing high traffic volume freeways. Group A^1 source locations are shown in Figure 2.

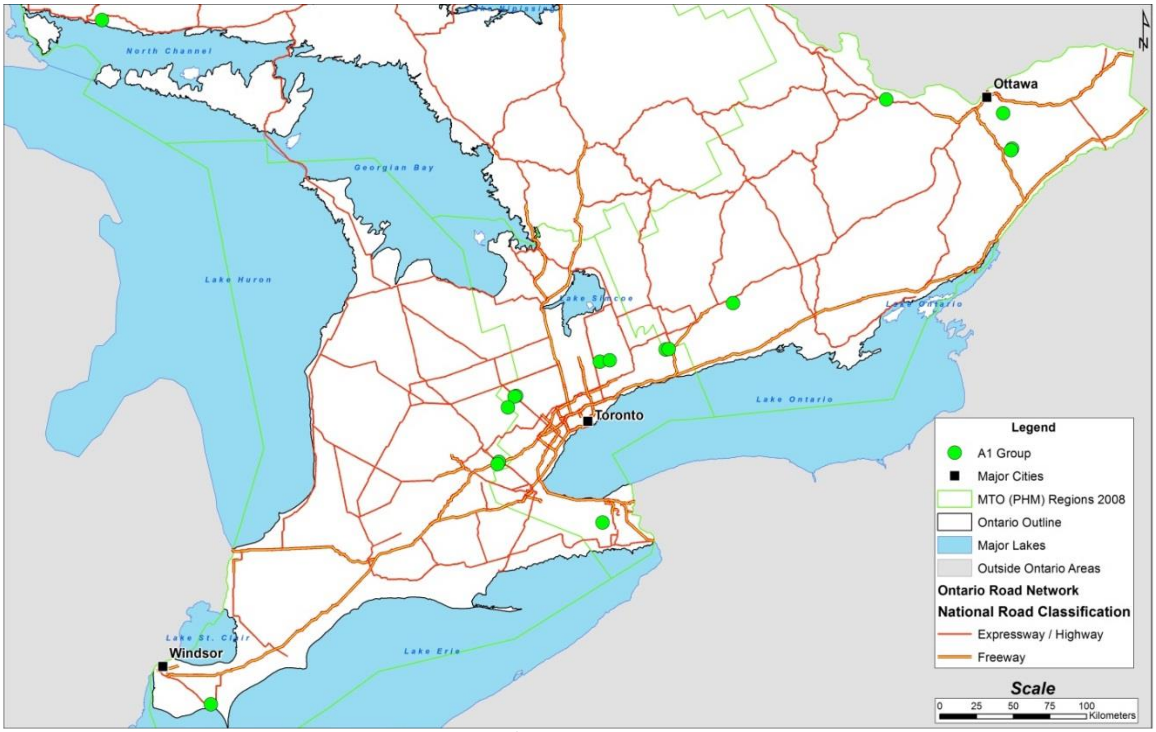

Figure 2: Group A^1 Aggregate Source Locations

4.1. Insoluble Residue Results

4.1.1 Total Insoluble Residue versus Retained 75µm Insoluble Residue

The MTO insoluble residue test (LS-613) reports two main results: 1) a total insoluble residue, or $\mathbf{IR_T}$; and 2) the insoluble residue retained on the 75µm sieve, or $\mathbf{IR_{R75}}$. Although the two results show excellent correlation (Figures 3 and 4), MTO has routinely used the IR_{R75} for purposes of source selection. There are several reasons for this; one is that the passing 75µm sieve (P75µm) portion of insoluble residue content (IR_{P75}) consists predominantly of silt and clay sized material that do not contribute significantly to pavement friction. Secondly, the difference between $\mathbf{IR_T}$ and $\mathbf{IR_{R75}}$ results can be considerable. In this study, differences between $\mathbf{IR_T}$ and $\mathbf{IR_{R75}}$ results reached a maximum near 7% in the Group A samples (Figure 5) and up to nearly 15% in the Group B samples (Figure 6). Almost half (43%) of the A samples have more than a 5% difference between $\mathbf{IR_T}$ and $\mathbf{IR_{R75}}$ results for the same sample tested (Figure 5). Almost 65% of the B samples have more than a 5% difference between $\mathbf{IR_T}$ and $\mathbf{IR_{R75}}$ results for the same sample tested (Figure 6).

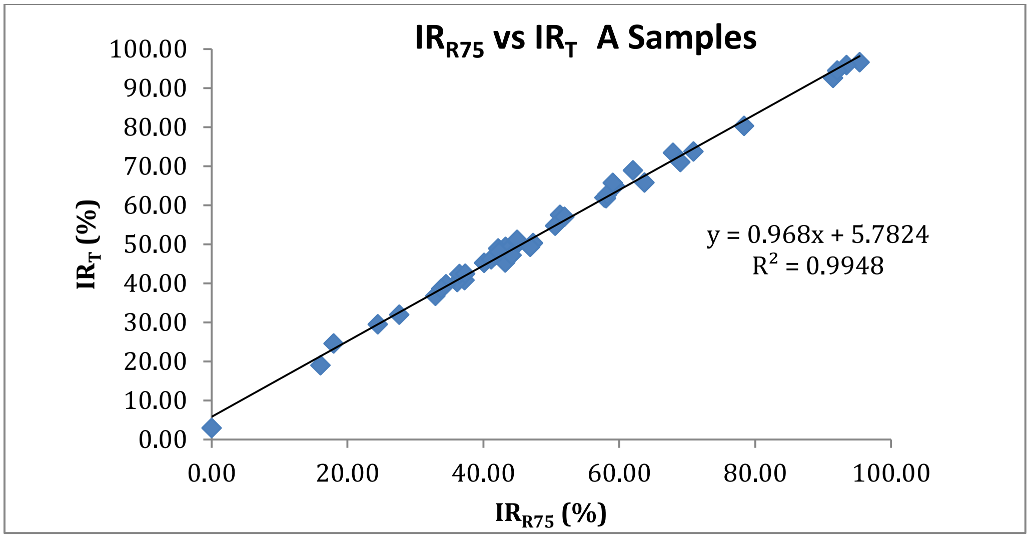

Figure 3: Reported IR_{R75} and IR_T values of A samples (n=44)

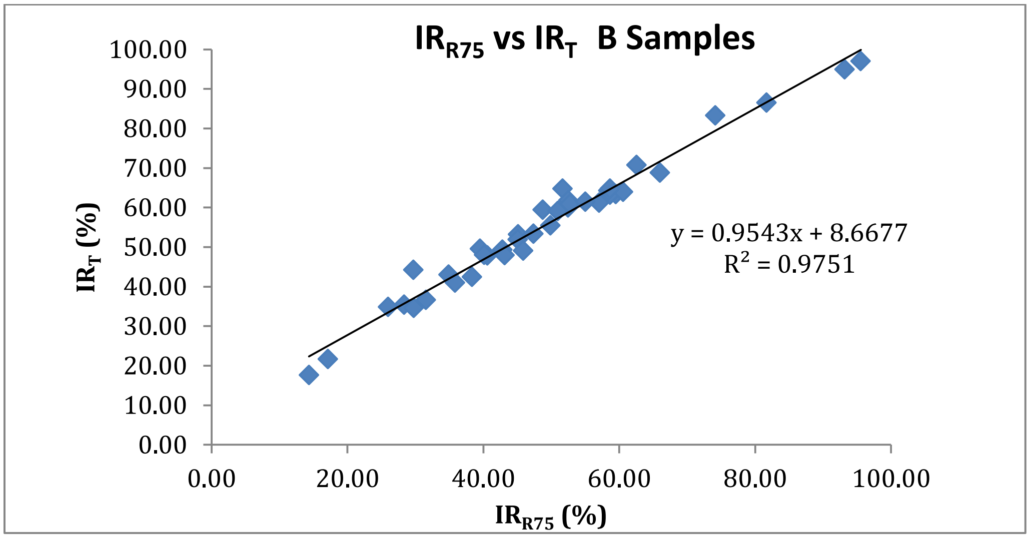

Figure 4: Reported IR_{R75} and IR_T values for the unprocessed samples (n=39)

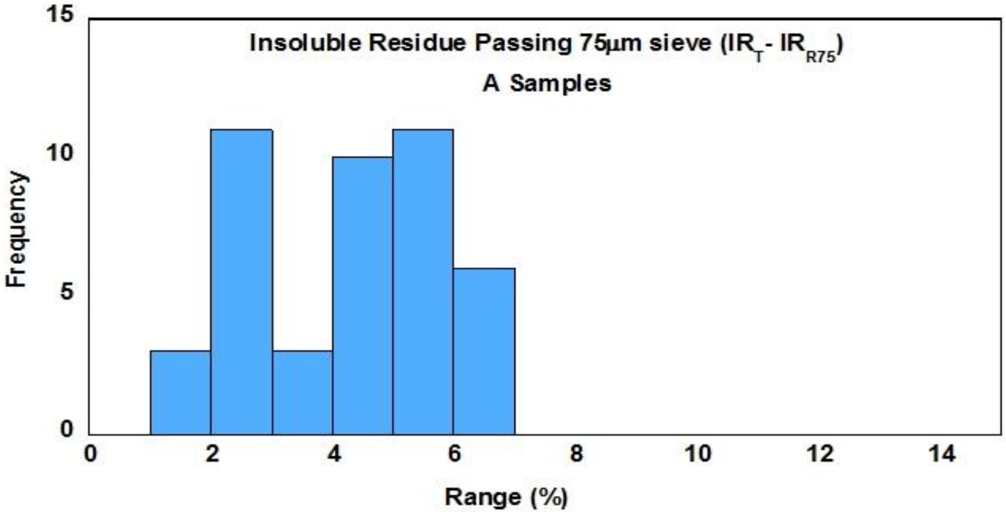

Figure 5: Difference between reported IR_T and IR_{R75} results for A samples. The difference is effectively the amount of residue passing the 75µm sieve (IR_{P75}).

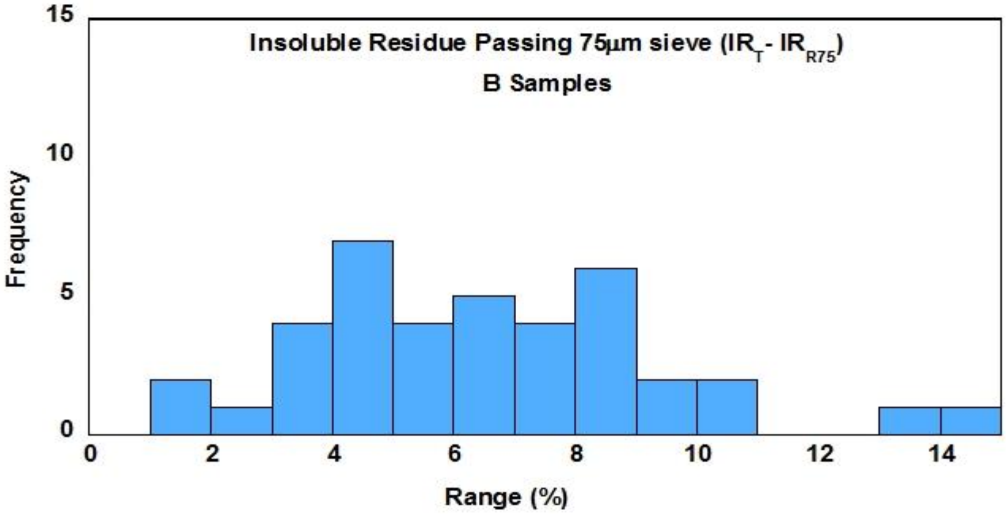

Figure 6: Difference between reported IR_T and IR_{R75} results for B samples (unprocessed materials). The difference is effectively the amount of residue passing the 75µm sieve (IR_{P75}).

Carbonate coarse and fine aggregates are known to polish under traffic wear (Rogers et al., 2003). These types of carbonate aggregates can often produce significant amounts of residue during the IR test, most of which is concentrated in the P75µm fraction (**IR_{P75} = IR_T - IR_{R75}**). The **IR_T** values for carbonate rock types can commonly be in excess of 3%, and even greater than 10% as in the case of many quarried Ontario limestones and dolostones, e.g., Spratt limestone, Pittsburg dolomitic limestone, where most of the residue is concentrated in the P75µm size range (Rogers and MacDonald, 2012). In these cases the residue typically consists of argillaceous and other detrital minerals such as clay minerals, mica, zircon, sulphide minerals, and quartz. Several of these materials are of low hardness and/or are of insignificant size to contribute to the "sandpaper like feel" that is surface micro-texture and its retention.

Relative large differences in **IR_T** and **IR_{R75}** values reported for carbonate and carbonate dominant materials may indicate a higher than desirable shale or argillaceous content. If this is the case, often large differences in **IR_T** and **IR_{R75}** may correlate with higher losses in Micro-deval Abrasion test results.

Alternatively, excessive amounts of P75µm material in the as received material may also affect this. Both the former and the latter should be well controlled in the case of concrete sand products due to strict physical property and gradation limits enforced by the specification. A weak to moderate correlation is observed between the **IR$_{P75}$** and Micro-deval abrasion losses for both the A and B samples (Figures 7 and 8).

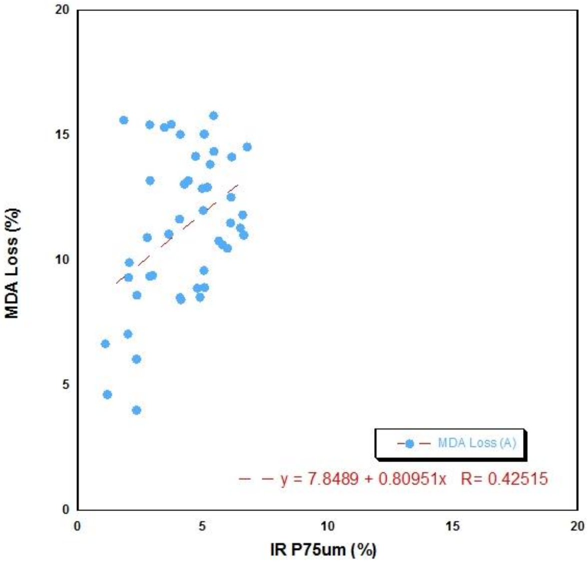

Figure 7: MDA Loss vs IR P75um – A Samples

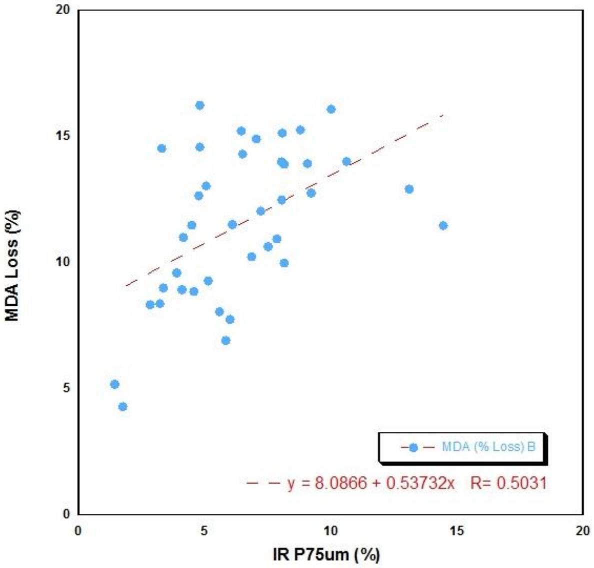

Figure 8: MDA Loss vs IR P75um – B Samples

4.1.2 IR$_{R75}$ Results and MTO Specification Limits

Figure 10 shows the general distribution of the IR$_{R75}$ test results for Group A samples. Approximately **23%** of Group A samples have IR$_{R75}$ test results above 60% (Figure 9). This indicates that almost one in four sources of concrete fine aggregate in southern Ontario and within close proximity to southern Ontario markets has the capability to produce material meeting the new IR requirements. In addition, many Group A samples are close to meeting the minimum 60% IR$_{R75}$ requirement, with approximately **18%** of samples having **IR$_{R75}$** results in the 50-60% range (Figure 9). These suppliers are within reach of the specification limit and may be able to achieve the target through modifications to their production process or by blending with small amounts of silicate-rich materials. Approximately **32%** of Group A samples have **IR$_{R75}$** results in the 40-50% range (Figure 9). These suppliers are also within reach of the specification limit and may too benefit from the new blending allowance. Locations of Group A sample sources demonstrating capability to meet the minimum 60% IR$_{R75}$ requirement, as well as other ranges are shown in Figure 10.

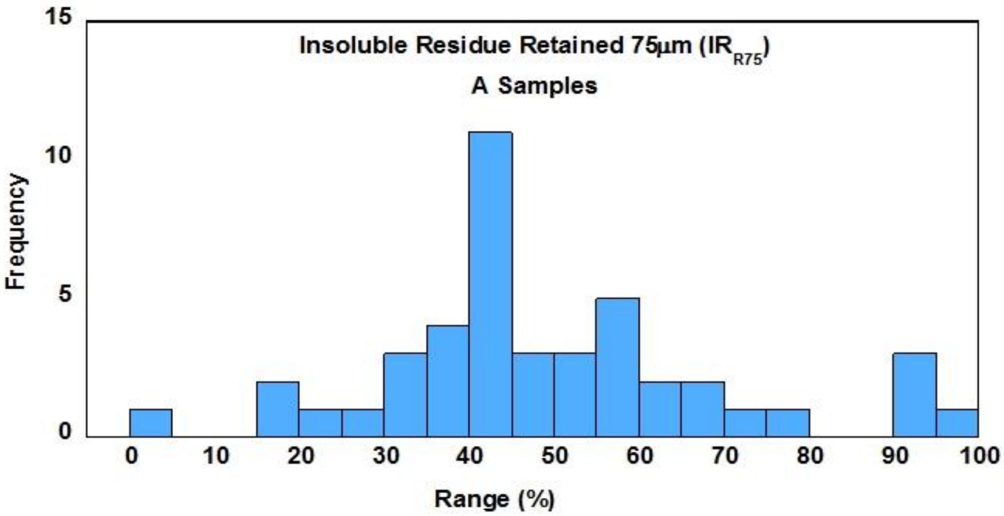

Figure 9: Distribution of IR$_{R75}$ values for A Samples (n=44)

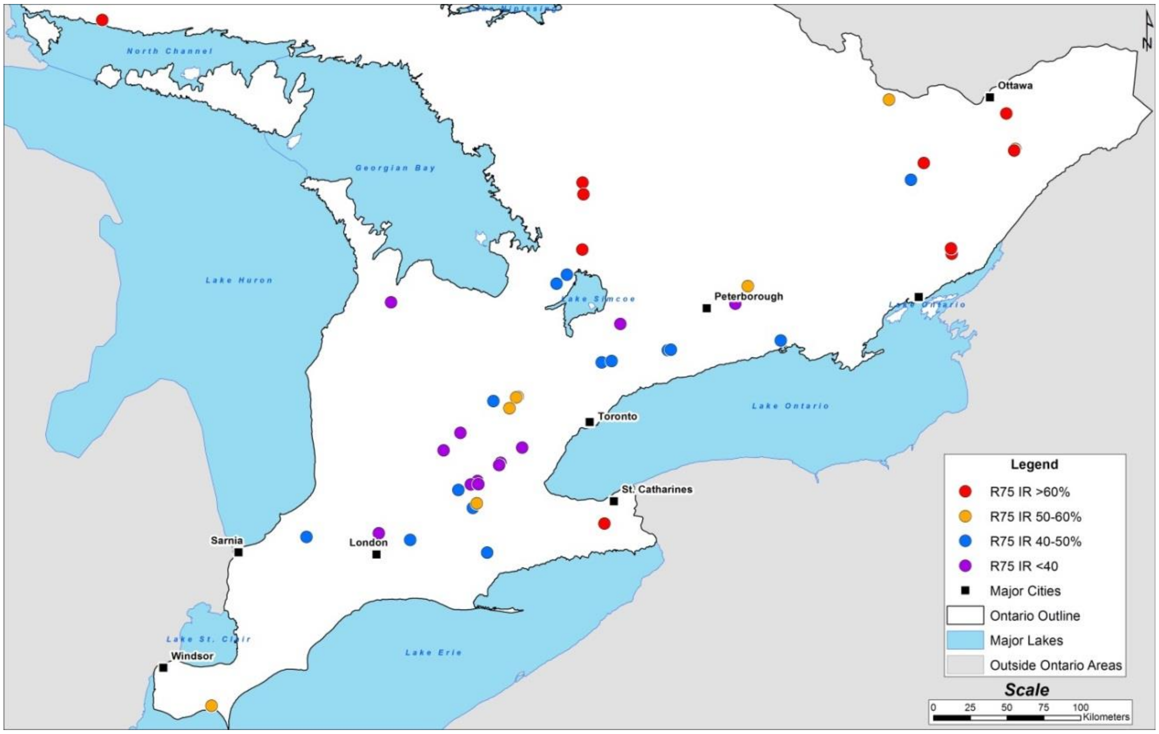

Figure 10. Geographic distribution of IR$_{R75}$ results for the Group A samples. Illustration of sources by insoluble IR$_{R75}$ content ranges (n=44)

Figure 11 shows the general distribution of IR$_{R75}$ test results for Group A^1 samples. Approximately **24%** of Group A^1 samples have IR$_{R75}$ test results above 60% (Figure 11). In addition **35%** of Group A^1 IR$_{R75}$ test results are within the 50-60% range, and **23%** are within the 40-50% range (Figure 11).

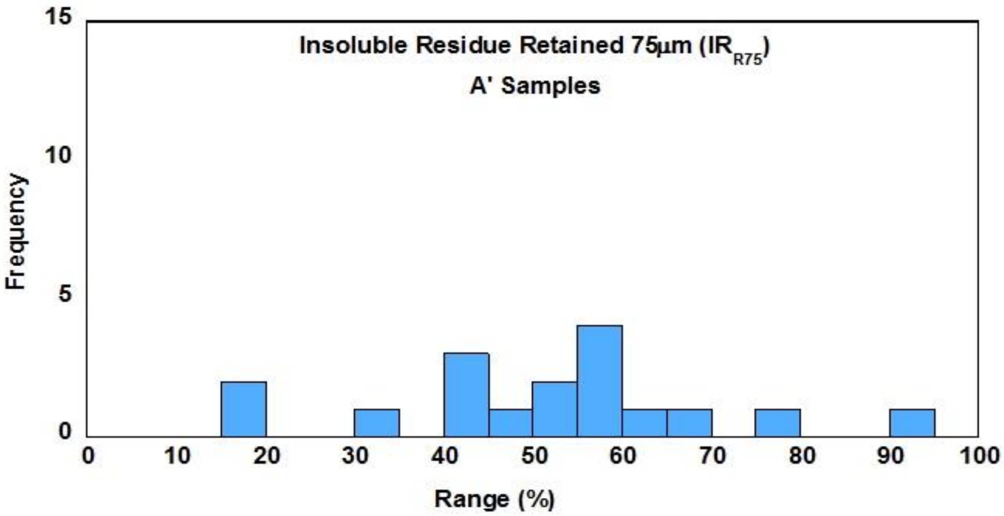

Figure 11: Distribution of IR$_{R75}$ values for A^1 Samples (n=17)

Figure 12 shows the general distribution of IR$_{R75}$ test results for Group B samples. Approximately **18%** of Group B samples have IR$_{R75}$ test results above 60% (Figure 12). In addition **28%** of Group B IR$_{R75}$ test results are within the 50-60% range, and **26%** are within the 40-50% range (Figure 12). Ranges of **IR$_{R75}$** for the different sample groupings are also summarized in Table 5.

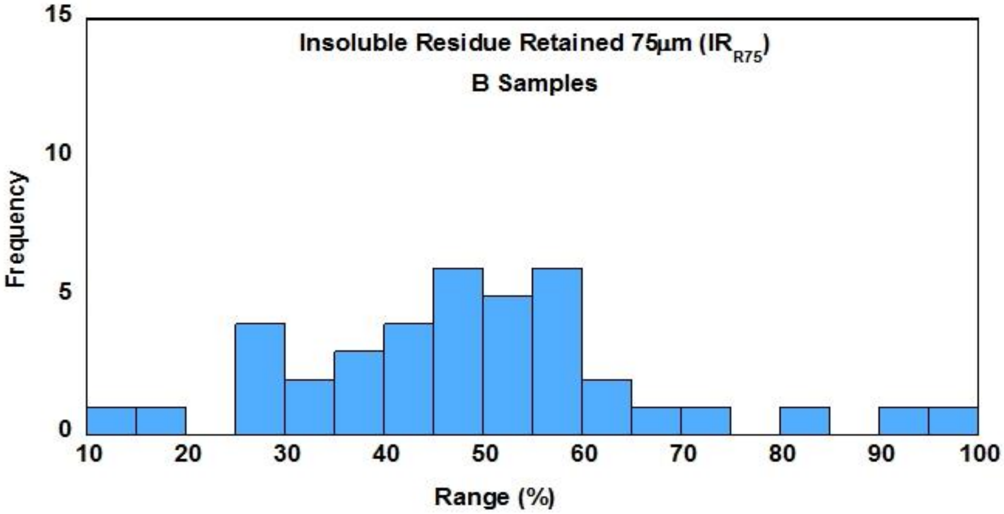

Figure 12: Distribution of IR$_{R75}$ values for B Samples (n=39)

Table 5. Summary of **IR_{R75}** ranges for the different sample groupings.

Group	IR_{R75} Range	%	n	Total
A	>60%	23	10	44
	50-60%	18	8	
	40-50%	32	14	
	<40%	27	12	
A^1	>60%	24	4	17
	50-60%	35	6	
	40-50%	23.5	4	
	<40%	17.5	3	
B	>60%	18	7	39
	50-60%	28	11	
	40-50%	26	10	
	<40%	28	11	

4.2. Geological Framework

Sources from which samples were collected were classified based on their surficial and/or bedrock geology using publications from the Ontario Geological Survey (Armstrong and Dodge, 2007; Ontario Geological Survey, 2003 and 2011). A summary of the geological classification of the sources sampled is included in Table 6.

Table 6 below outlines the geological context of the sources sampled, and are grouped by the dominant surficial geology landform or depositional environment. The different surficial geology deposit categories used were: beach, delta, ice-contact, outwash, and mixed provenance. The three bedrock sources sampled are subdivided by rock type. Outwash and ice contact are the predominant geology observed in the sample set, with ice contact performing better than average at the 60% IR_{R75} level while outwash performing poorly at the 60% IR_{R75} level.

Table 6: Insoluble Residue Results of A Samples with Geology

Geology	n	IR_{R75} Range			
		>60%	50-60%	40-50%	<40%
Beach	7	2	3	2	
Delta	1	1			
Ice Contact	15	5		7	3
Mixed	3			1	2
Outwash	15		5	4	6
Carbonate Bedrock	1				1
Siliceous Bedrock	2	2			
Totals	**44**	**10**	**8**	**14**	**12**

4.3. Fine Aggregate Production Impacts on Insoluble Residue Tests

One of the goals of this program was investigation of the effects of production process on the insoluble residue content of concrete sands. To study this, the **IR_{R75}** results of the A and B samples were compared for 39 sources. Figure 13 shows 22 of the sources that had an increase in **IR_{R75}** content as a result of processing operations. This data shows that there is a strong correlation between the processed and unprocessed samples, and that current processing operations can improve insoluble residue results. On average there was a 6% increase to insoluble residue for the 22 sources. Therefore current processing operations add another option for the supplier when planning for insoluble residue requirements.

Figure 14 shows all 39 sources that had both an A sample (processed) and a B sample (unprocessed), with the relative increase or decrease in IR_{R75} results that occurred as a result of processing on the X-axis. A negative effect indicates that processing operations resulted in a net decrease in the **IR_{R75}** of a final concrete sand product as compared with the "raw feed". A positive effect indicates that processing operations had the result of increasing the **IR_{R75}** content of the final product.

In general, sources that could be classed geologically as outwash tended to show increases in insoluble residue results as a function of processing operations (Figure 14). Sources classed as ice contact deposits tended to show decreases in insoluble residue results after processing operations (Figure 14).

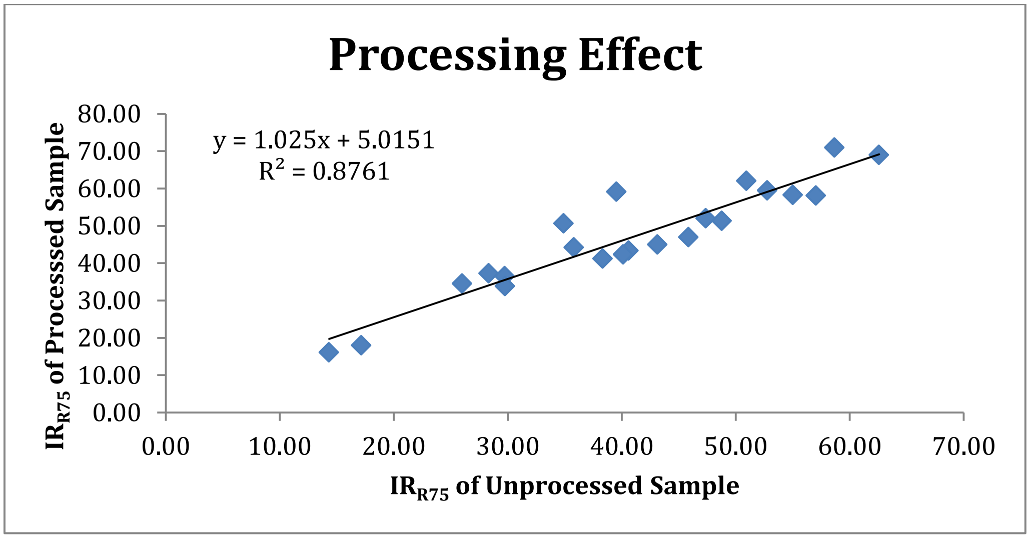

Figure 13: Processing Effect on a Subset of Group 1 (n=22)

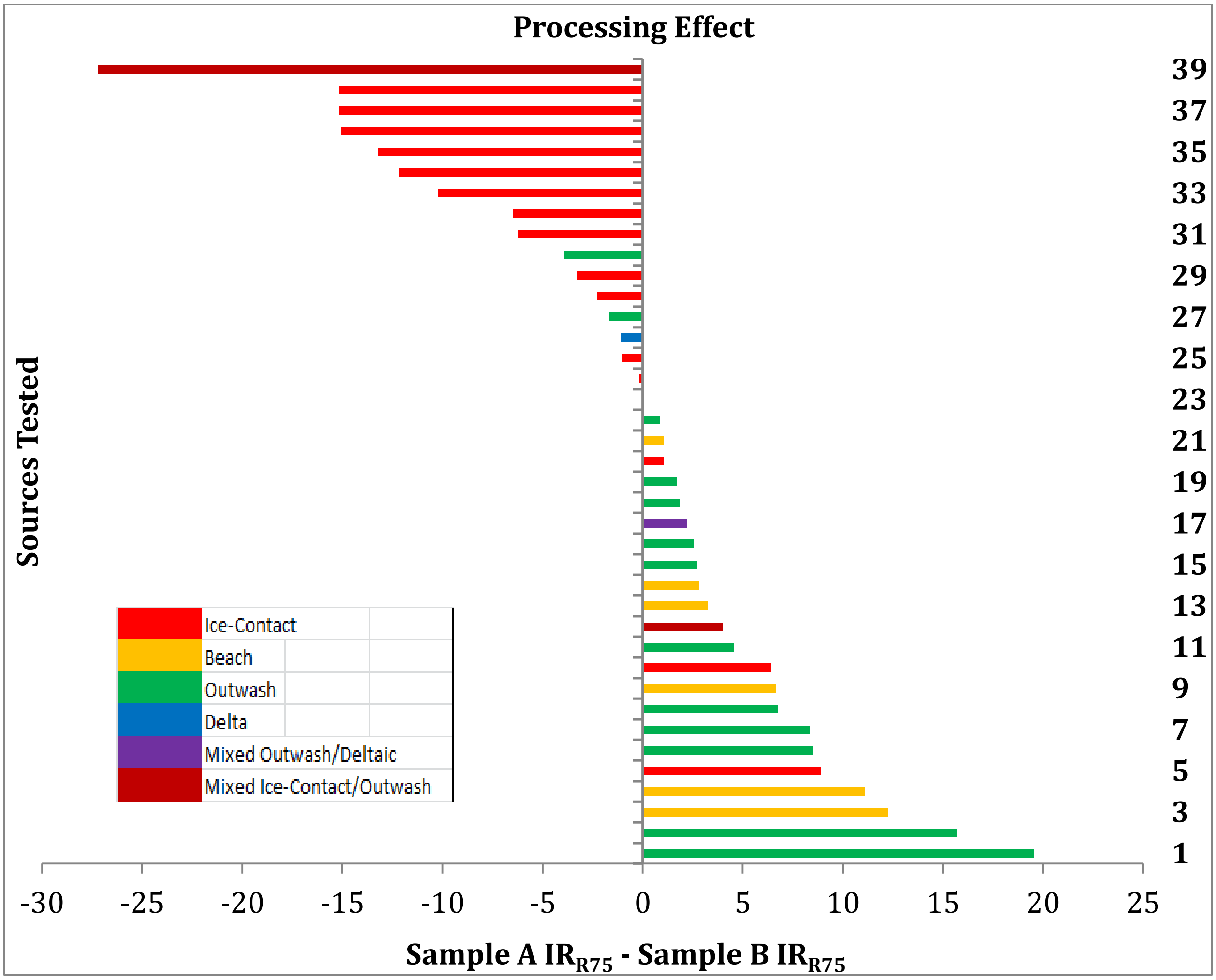

Figure 14: Difference in IR_{R75} between Unprocessed (Sample B) and Processed (Sample A) Samples (n=39)

It is important to note that this analysis does not differentiate between production methods, the amount of screenings added, and the mineralogy of the screenings. Further testing with more strict control would be necessary to analyse the effect of processing in more detail.

4.4. Correlation with Other Test Methods

Micro-Deval Abrasion (MDA)

Previous studies have shown that the Micro-deval abrasion test correlates well with the amount of poor or weak rock types (Rogers et al, 1991). Group A samples are primarily made up of silicate or carbonate rocks and minerals (determined by petrographic evaluation), and do not show any correlation between MDA and IR testing. This may be due to the presence of durable carbonates which may not break down during MDA testing but will dissolve during acid digestion.

Fowler and Rachad (2012) showed significant negative correlation between decreasing acid insoluble residue results and increasing Micro-deval abrasion losses ($R^2 = 0.8091$). This is generally not the case with this study because most materials sampled are of high quality concrete fine aggregates and/or the raw feed that is used to produce them (Figure 16). Fowler's study contained several materials that showed MDA losses in excess of 18%, up to 27%. It is possible we would have seen similar results if poorer quality materials had been tested in this study. The strict physical property and gradation limits enforced by MTO's specification usually preclude the use of these undesirable poorer quality materials.

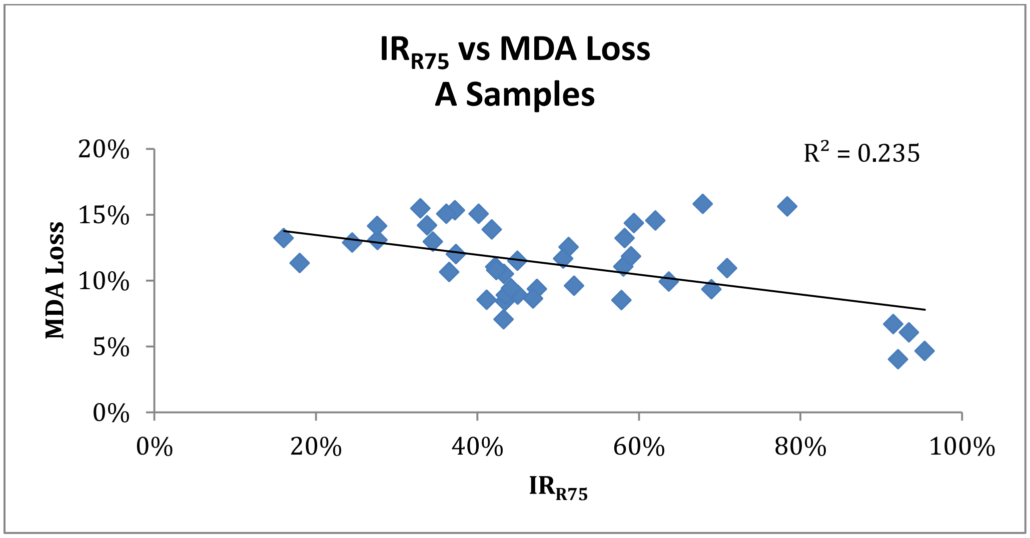

Figure 15: Micro-deval abrasion loss versus IR_{R75} results for A samples (processed materials).

Petrographic Analysis

A strong correlation exists between IR results and carbonate content determined by petrographic evaluation, Figure 12 shows the results obtained from Group A samples. Although not shown here, a benefit of the petrographic analysis over the IR test is that it provides additional detailed rock type and mineralogical breakdowns for the entire sample as well as for individual sieve fractions. A summary of the data is provided in Table 7.

Table 7: Petrographic Analysis Results Summary

Category	Min (%)	Max (%)	Average (%)
Silicate rocks and minerals	1.4	99.8	50.6
Carbonate rocks and minerals	0.0	98.6	46.7
Shale, argillite, clay, ochre	0.0	2.1	0.1
Micaceous minerals	0.0	10.9	1.2
Chert, flint, jasper	0.0	9.9	0.8
Cemented particles	0.0	5.4	0.6
Sulphate rocks and minerals	0.0	0.0	0.0
Sulphide rocks and minerals	0.0	0.2	0.0
Oxide minerals	0.0	0.1	0.0

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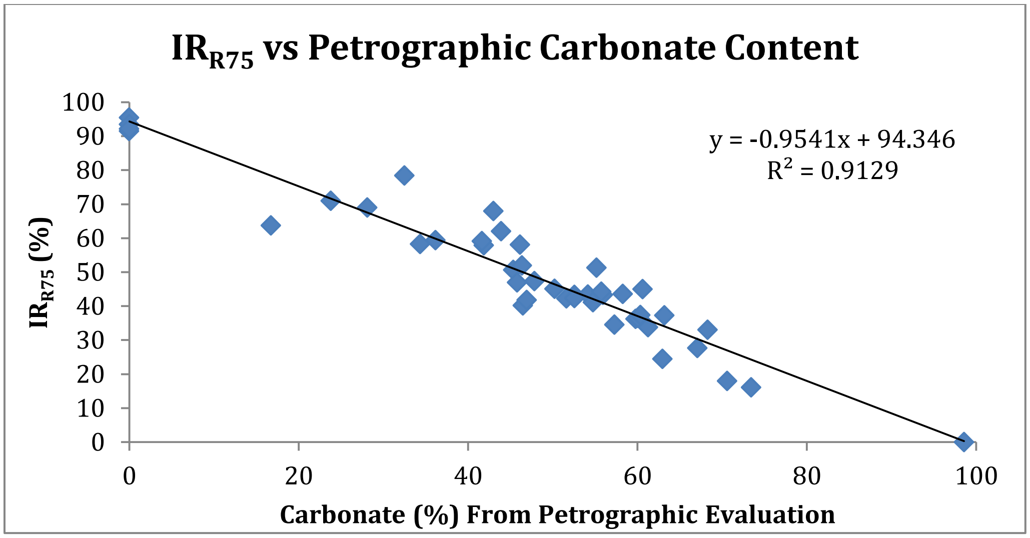

Figure 16: Carbonate Content of the A Group samples

5. Conclusion

Construction material selection has to balance many different factors including; available supply, distance to markets, durability, safety, and cost. This project provides new information regarding the availability of concrete fine aggregate and insoluble residue requirements for use in exposed Portland cement concrete pavements.

The project has shown that at least **23%** of sources currently producing concrete fine aggregate for the southern Ontario market are capable of successfully meeting a minimum 60% IR$_{R75}$ requirement. An additional **18%** of current suppliers are capable of achieving 50 to 60% IR$_{R75}$ results. These suppliers that fall just short of the 60% IR$_{R75}$ target may benefit from adjustment of their processing operations and/or a minor amount of blending. An IR$_{R75}$ range of 40-50% was achievable for **32%** of the currently producing concrete fine aggregate sources. These suppliers are also within reach of the specification limit and may benefit from the new blending allowance, which will provide many suppliers the opportunity to produce material for future exposed PCC pavement contracts.

Material processing has shown to have a noticeable impact on the final insoluble residue content. Over half of the sources showed a beneficial impact in relation to insoluble residue targets, with a noticeable beneficial trend for outwash sources. This effect allows some suppliers to increase insoluble residue results simply by using current processing techniques. This trend should be investigated further to optimize this advantage.

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