The TOSS does have higher PG values for both the high and low temperatures than the MWSS, which could be explained by the additional aging induced by exposure to oxidation, solar radiation and high temperatures. There are also observable differences between the two RAP sources. It is evident from table 2 that it is not practical to construct an HMA pavement using only recycled asphalt binder derived from RAS as few pavements experience temperatures up to 108°C (226°F) and many states experience temperatures cooler than 6°C (42.8°F). Due to the fact that TOSS and MWSS are 'stiffer' than what is commonly used in HMA pavements, they are incorporated into the HMA pavement along with the less stiff RAP and the virgin asphalt binder.

Table.3 shows the continuous PG grading of the binder extracted from laboratory prepared mixture specimens. It can be seen that the addition of RAP and/or RAS consistently increases the high and low temperature PG grades. This is not surprising as the composite binder experiences complete mixing in the extraction/recovery process.

Table.3. RAS Mixture Binder Performance Grade (PG) Binder Grading (1)

Mix #	Mix Identification	High PG Temp	Low PG Temp	Continuous PG Grade	PG Grade
1	PG 58-28 Control	63.7	-31.0	63.7 -31.0	58-28
2	15% RAP	72.4	-20.9	72.4 -20.9	70-16
3	25% RAP	77.2	-19.7	77.2 -19.7	76-16
4	30% RAP	75.4	-25.6	75.4 -25.6	70-22
5	15% RAP 5% MWSS	78.7	-16.7	78.7 -16.7	76-16
6	15% RAP 5% TOSS	80.1	-16.3	80.1-16.3	76-16
7	25% RAP 5% TOSS	84.6	-14.1	84.6 -14.1	82-10
8	25% RAP 5% MWSS	79.3	-18.7	79.3 -18.7	76-16
9	25% RAP 5% TOSS 51-34	75.9	-21.9	75.9 -21.9	70-16
10	25% RAP 5% MWSS 51-34	75.1	-23.2	75.1 -23.2	70-22
11	25% RAP 3% TOSS	81.0	-17.5	81.0 -17.5	76-16
12	25% RAP 3% MWSS	79.5	-18.2	77.2 -18.2	76-16
13	15% RAP 3% TOSS	78.1	-18.6	78.1 -18.6	76-16
14	15% RAP 3% MWSS	78.5	-19.2	78.5 -19.2	76-16
15	10% RAP 5% TOSS	77.7	-17.1	77.7-17.1	76-16
16	15% RAP2 5% TOSS	79.4	-20.3	79.4-20.3	76-16
17	5% TOSS	75.6	-24.2	75.6-24.2	70-22

As an example consider mix number 7, the high PG temperature of the composite binder of 84ºC is higher than the 58ºC of the virgin binder and even slightly higher than 80ºC of the RAP, but is much less than the 108ºC of the TOSS. A similar observation can be made of the low PG temperature as well; the overall composite binder low temperature of -14ºC is greater than the -28ºC of virgin binder, slightly greater than the -17ºC of the RAP, but less than the -11ºC of the TOSS. The resultant low temperature properties of the composite binder may not be flexible enough to resist thermal cracking, a major concern for Minnesota. The dramatic increase of the low temperature PG grade of the composite asphalt binder could possibly be mitigated by using a 'softer' virgin asphalt binder as demonstrated by mix numbers 9 and 10. Consider mix 9, which has the same amount and type of RAS and RAP as mix 7, but a virgin binder low temperature of -34ºC as opposed to -28 ºC, this difference has significant effect on the low temperature properties of the composite binder, lowering it from -14ºC to nearly - 22ºC.

The type of RAS doesn't appear to have a significant effect on the low temperature PG grade at the 15% RAP and 3% RAS concentration. Note that HMA producers did not think adding 3% RAS to a mixture was practical, 5% was the minimum practical concentration that could be added to a mix (outside of a laboratory). When the RAP content is 25% and the RAS content is 5% there is a visible difference between mixtures containing TOSS vs. MWSS as shown in the difference in both high and low composite binder PG temperatures of mixes 7 and 8.

Asphalt Mixture Testing

The dynamic modulus test was performed on a minimum of two samples representing each of the 17 mixtures containing various amounts of RAS and RAP as described earlier. The testing was performed in accordance with AASHTO TP62 which included six loading frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) and five temperatures (10, 40, 70,100 and 130 ºF). Mixtures containing the PG 51-34 binder could not be tested at the highest temperature (130 ºF), due to the softness of the mixture preventing a secure fit of the LVDTs.

This testing is invaluable in comparing the mixture's performance as the mixture master curves capture how well the RAS/RAP binder mixes with the new, or virgin, asphalt binder. In general, the modulus increases as RAP content increases and these differences appear to be more pronounced at the lower frequencies (higher temperatures) than the higher frequencies (lower test temperatures). The master curves were plotted on a set of logarithmic axes. This convention tends to graphically compress high numeric values and emphasize differences at low numeric values. Figure 6 shows mix 7 and 8, as well as the control mix, not surprisingly the addition of recycled materials stiffens the mixture. Mix 7 appears to be stiffer than Mix 8, suggesting that TOSS has a stiffer binder than the MWSS, which is expected due to the increased aging of TOSS through long term exposure to oxidation, solar radiation and high temperatures, which was confirmed earlier through binder extraction and gradation (Table 2). In addition, due to the coarse gradation, the MWSS binder is contributing less to the mixture than the finely ground TOSS binder. Not only is the TOSS asphalt binder stiffer, a greater portion of it is mixing with the virgin asphalt binder than the MWSS asphalt binder. It is interesting to note the difference between the control (Mix 1) and Mix 8 appears to be similar as the difference between Mix 7 and Mix 8 at certain frequencies, which is a very significant difference. This large difference in performance between the MWSS and TOSS RAS sources was not expected to be as large as the difference between a virgin mix and a MWSS mix.

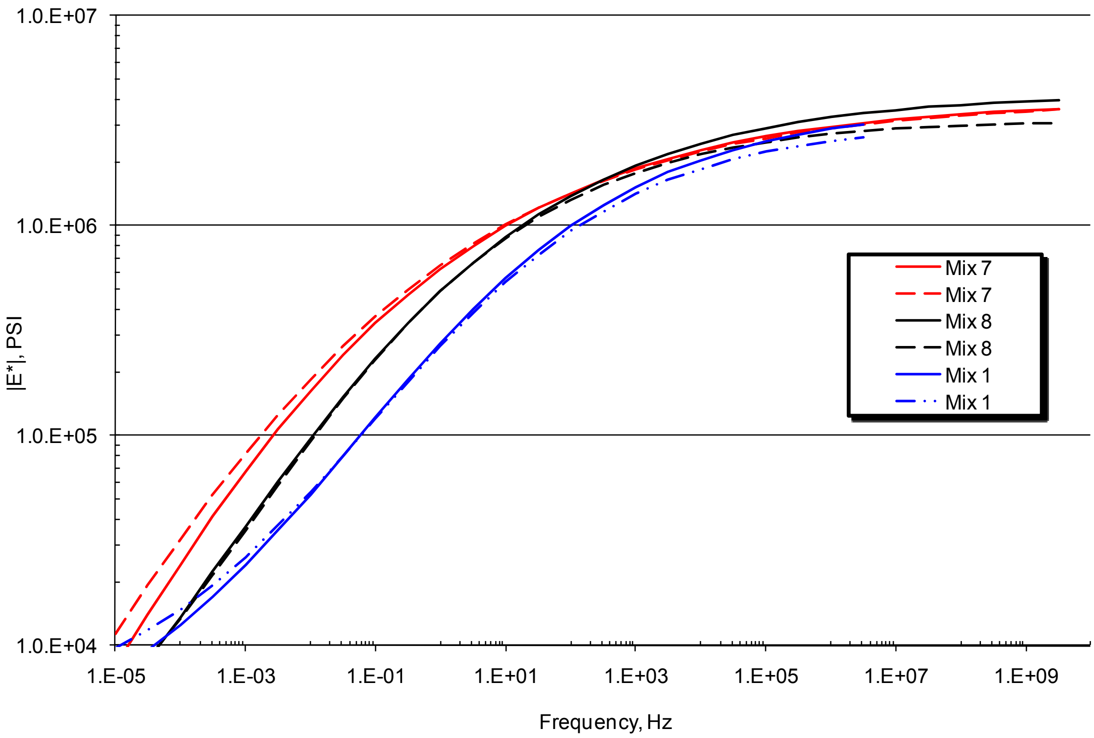

Figure 6. |E*| of Mix 1, Mix 7 (25% RAP/5% TOSS) and Mix 8 (25% RAP/5% MWSS)

Figure 7 shows the master curves of mix 7 and 9 both of which contain 25% RAP and 5% TOSS and are identical except that mix 7 has a virgin asphalt binder of PG 58-28 and mix 9 has a PG 51-34. The impact of the softer virgin asphalt binder is evident as mix 9 has lower modulus values than mix 7, indicating that it's less stiff.

Dynamic modulus tests demonstrated that TOSS is stiffer than MWSS. The difference between the two RAS sources was most pronounced at the 5% level, and was apparent regardless of RAP concentrations. The largest ratios among modulus values were observed at the lower frequencies, which corresponded to the higher temperatures. The dynamic modulus testing did not test at temperatures low enough to effectively characterize low temperature cracking. Dynamic modulus testing also demonstrated that the stiffening effects TOSS alone appears to be much greater than RAP alone.

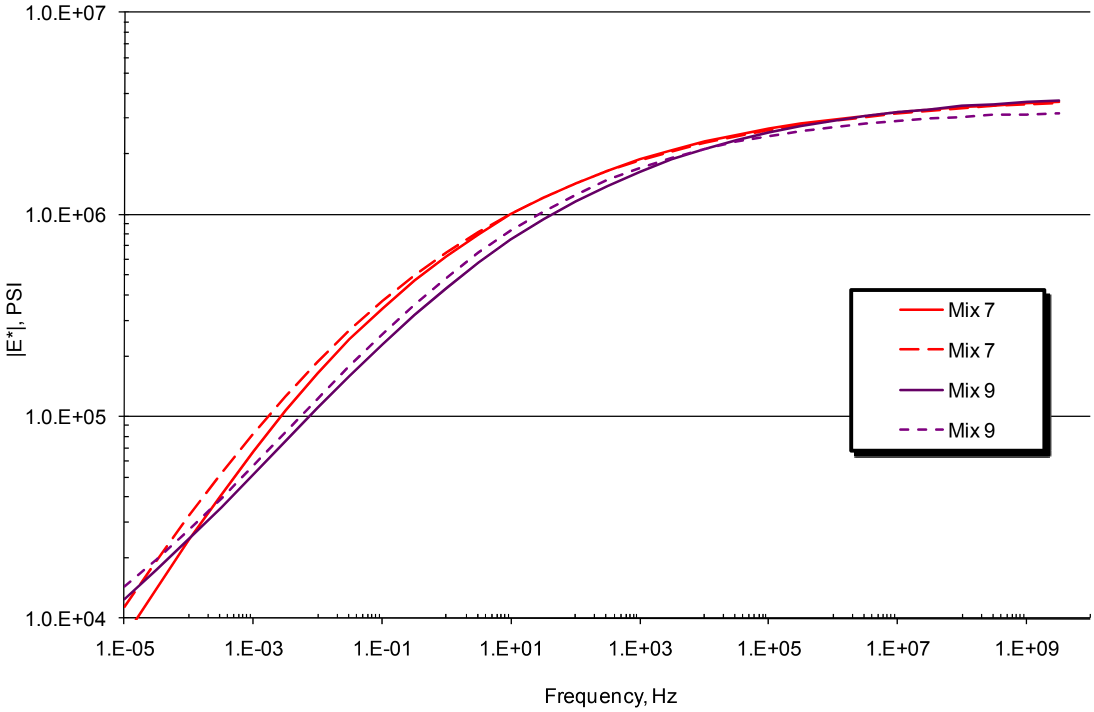

Figure 7. |E*| of Mix 7 (25% RAP/5% TOSS) and Mix 9 (25% RAP/5% TOSS)

Conclusions

Incorporating recycled materials into pavements has been motivated by both environmental concerns of rising landfill deposits of RAS and the financial concerns of rising construction and materials costs, especially asphalt binder. The incorporation of RAS into HMA pavement mixtures must be done so in a prudent manner to avoid unnecessary and costly premature pavement failures which could potentially jeopardize the widespread implementation of the technology.

There have been successful RAS/RAP projects that are performing adequately; however it only takes one failure to serve as a reminder of the potential negative effects of recycled materials on HMA durability. Dynamic modulus tests on laboratory produced mixtures for this study demonstrated that there is in fact, a significant difference in stiffness, especially at the lower frequencies (higher temperatures), between mixtures containing RAS/RAP and virgin mixtures. Thermal (low temperature) cracking heavily influences the durability of Minnesota HMA pavements. The low temperature binder PG grade was increased with the addition of RAP and RAS suggesting an increase in thermal cracking potential of the mixture. Thus RAS/RAP can and should be used in HMA pavement mixtures, but too much will compromise pavement durability.

Minnesota currently has a comprehensive RAS/RAP specification that does not require contractors to seek approval before using the recycled materials, which has expanded the use of MWSS. Mn/DOT's specification seeks to balance the economic and environmental benefits of using RAS/RAP against the impacts on pavement performance by limiting the total amount of material that can be incorporated and by requiring the material to meet gradation and deleterious material requirements.

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City of Saskatoon's Green Streets Program - A Case Study for the Implementation of Sustainable Roadway Rehabilitation with the Reuse of Concrete and Asphalt Rubble Materials

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Abstract

In 2006 the City of Saskatoon recognized that the large amounts of asphalt and concrete rubble materials stockpiled in its yards must be addressed. After experimenting with the material as a replacement backfill material with City forces, the City determined that improved engineering specifications and structural design processes needed to be implemented to facilitate the standard use of the recycled aggregates. In 2009, the City of Saskatoon developed the Green Streets Program to pilot the use of advanced mechanistic engineering and state of the art impact crushing of rubble materials for roadway construction. For the program to be considered successful value added processing, mechanistic-climatic characterization and sustainable holistic life cycle analysis had to be considered.

Based on the findings of the City of Saskatoon Green Streets Program, the City is now producing five types of high value specified crushed concrete materials, and three types of specified asphalt aggregate materials. These materials are being used as subbase, base course, drainage rock, stress dissipation layers and structural black base. From a mechanistic engineering characterization perspective, this research shows the crushed concrete and crushed asphalt aggregates are technically superior to conventional locally available aggregates.

The City of Saskatoon Green Streets Program identified many benefits achieved through the use of recycled materials in road construction on a technical, social, environmental and economic basis. Residents are provided a roadway with superior structural performance and waste rubble generated from aging city infrastructure is diverted from landfills. In addition, the cost savings generated by the Green Streets Project was determined to be approximately 55 percent through the structurally equivalent substitution of recycled aggregates for virgin sourced aggregates.

To further address the key aspects of road infrastructure sustainability the quantification of the energy used to rehabilitate roads and carbon generation during roadway rehabilitation will assist in quantifying the benefits of sustainable construction solutions. The future implementation of mechanistic based End Product Specifications will also ensure that the City will have a reliable engineering framework from which to employ innovative and sustainable road infrastructure solutions utilizing recycled road materials.

1 Introduction and Background

Like many municipalities, the City of Saskatoon is facing decreasing road level of service and decreasing road preservation budgets resulting in an infrastructure crisis. Much of the existing infrastructure has been in service beyond its original design life and has experienced severe climatic conditions as well as increased vehicle loadings which result in many roads requiring rehabilitation. In addition, recently constructed roads have also shown rapid deterioration to the point where rehabilitation is also required (Prang and Berthelot 2009).

Through utility and infrastructure repairs, the City of Saskatoon generates approximately 100,000 MT of hot mix asphalt concrete (HMAC) and Portland cement concrete (PCC) rubble each year (Berthelot et al. 2009). At the same time, landfill space is becoming more expensive and limited. Also, the lack of quality aggregate sources near Saskatoon is resulting in natural aggregate materials being hauled from distances up to 100 kilometres away. As infrastructure funding is not increasing rapidly enough to respond to the growing infrastructure deficit and cost of construction and materials, innovative methods of rehabilitation must be developed to allow more rehabilitation to occur to close the infrastructure gap.

For a number of years prior to 2006, the City of Saskatoon stockpiled HMAC and PCC rubble until it had a sufficient amount of rubble to warrant issuing a contract to crush the material. In the past, difficulties crushing HMAC rubble was experienced due to contamination in the stockpile. The crushed material was used as a marginal quality fill material.

In 2008, due to increasing construction prices and the large amounts of rubble available in City stockpiles, the City decided to investigate processing rubble materials into recycled aggregates for use as a replacement for base course aggregate in roadways. In 2009, the City realized there was a potential to crush the rubble material into a high quality aggregate that could be used within roadway construction as a structural system. However to accomplish this, the City of Saskatoon would have to implement improved engineering specifications to facilitate the proper use of the recycled aggregate. The result of this realization was the creation of the City of Saskatoon's Green Streets Program.

2 Key Technical Aspects of Green Streets

For the Green Streets Program to be successful, key technical aspects of roadway materials and construction were considered in three areas of research:

1. Value added processing of rubble materials through crushing into high quality road construction materials in order to meet the traditional City of Saskatoon gradation specifications,

2. Mechanistic-climatic characterization of the recycled materials to develop a sound scientific design and materials specification process that is based on engineering mechanics, and;
3. Quantification of the holistic life cycle and long term sustainability of Green Street Technology.

The purpose of this paper is to summarize these key technical aspects of the City of Saskatoon's Green Streets Program in the context of sustainability.

2.1 Value Added Processing

Past efforts by the City of Saskatoon to crush concrete resulted in only one type of 50 mm minus subbase material used as a low quality backfill material. This type of low quality end product material is currently the most common recycled concrete product. By refining the crushing process and conducting pre-processing for deleterious materials, a number of high quality products can be processed that meet the current City of Saskatoon gradation specifications for natural aggregates.

Berthelot et al. (2010) found that an impact crusher produced superior end product aggregate from diverse sources of rubble material compared to the traditional jaw and cone type crushing equipment. Due to of the amount of contamination and subgrade fines, the use of the traditional jaw-cone crushing resulted in materials that were high in fines relative to City of Saskatoon base course specifications. Economically sufficient production rates were not achieved using conventional jaw and cone crushing due to difficulties processing rubble materials containing residual asphalt cement content and/or reinforcing steel.

To produce high quality aggregates that meet the City of Saskatoon gradation standards with economically sufficient production rates, an impact crusher with a magnetic metallic extruder and screener was implemented. Upstream processing which involved the removal of reinforcing steel and other waste materials and breaking down of the materials to a proper size for feeding into the crusher resulted in reduced fines in all of the end products. The production rate with this crushing equipment configuration was found to be on average between 100 MT and 200 MT per hour (Berthelot et al. 2009). Figure 1 illustrates the state-of-the-art impact crusher and screening system used and the ability to produce several high quality materials simultaneously.

Figure 1: State-of-the-art Impact Crusher, Producing Five Specified Materials with no Waste

Based on the findings of the Green Streets Program, the City of Saskatoon is now producing five high quality crushed PCC materials and three HMAC materials. The end-use of each product is summarized in Table 1, and Table 2. The unit cost of production for the PCC and HMAC products is \$12/MT and \$9/MT, respectively (PSI Technologies 2010). The subbase material that is produced is comprised of material removed by a grizzly screen in the pre-processing phase. The removal of these materials assists with keeping the fines content low in the other produced materials.

Table 1: Crushed Portland Cement Concrete (PCC) Materials

Material	Use
50mm Well Graded (GW) High Fines PCC	Subbase
19mm Well Graded PCC	Base Course
25mm Open Graded Base Course (OGBC) PCC Rock	Structural Base Course / Drainage
65mm Crushed Open Graded PCC Rock	Drainage / Stress Dissipation
150mm Crushed Rock	Rip Rap and Drainage

Table 2: Crushed Hot Mix Asphalt Concrete (HMAC) Materials

Material	Use
19mm Well Graded HMAC	Structural Black Base
25mm Crushed Open Graded HMAC Rock	Structural Black Base
65mm Crushed Open Graded HMAC Rock	Drainage /Stress Dissipation Layer

The recycled materials produced with the impact crusher met the City of Saskatoon well graded and crushed rock material gradation specifications for traditional aggregates. The gradations of the recycled PCC and HMAC produced aggregates are presented in Figure 2 and Figure 3.

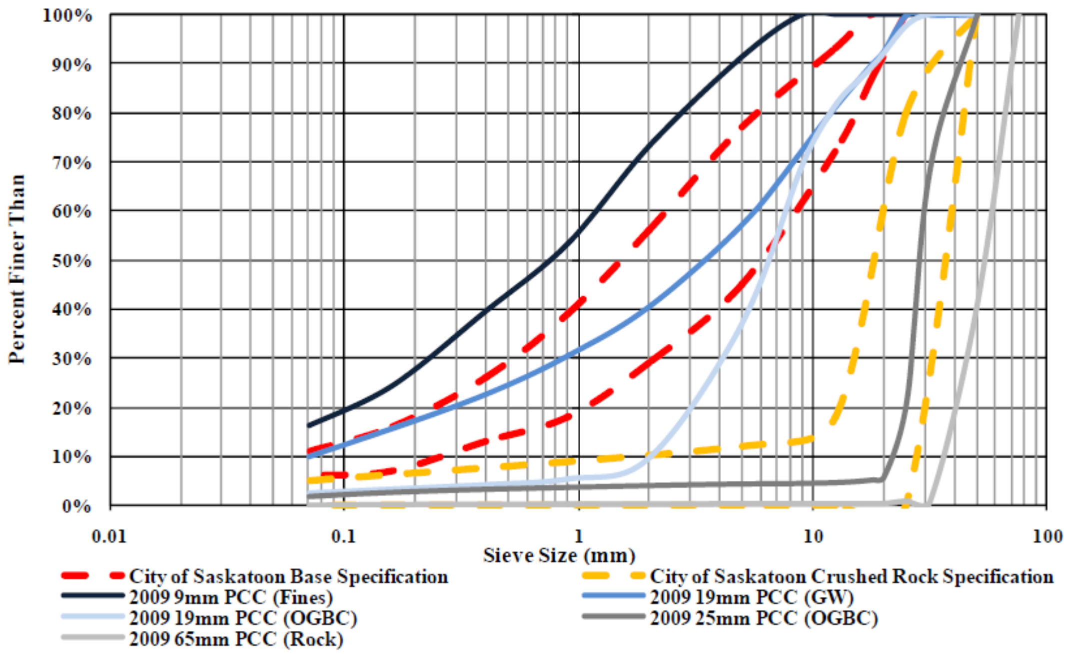

Figure 2: Crushed Portland Cement Concrete (PCC) Grain Size Distribution

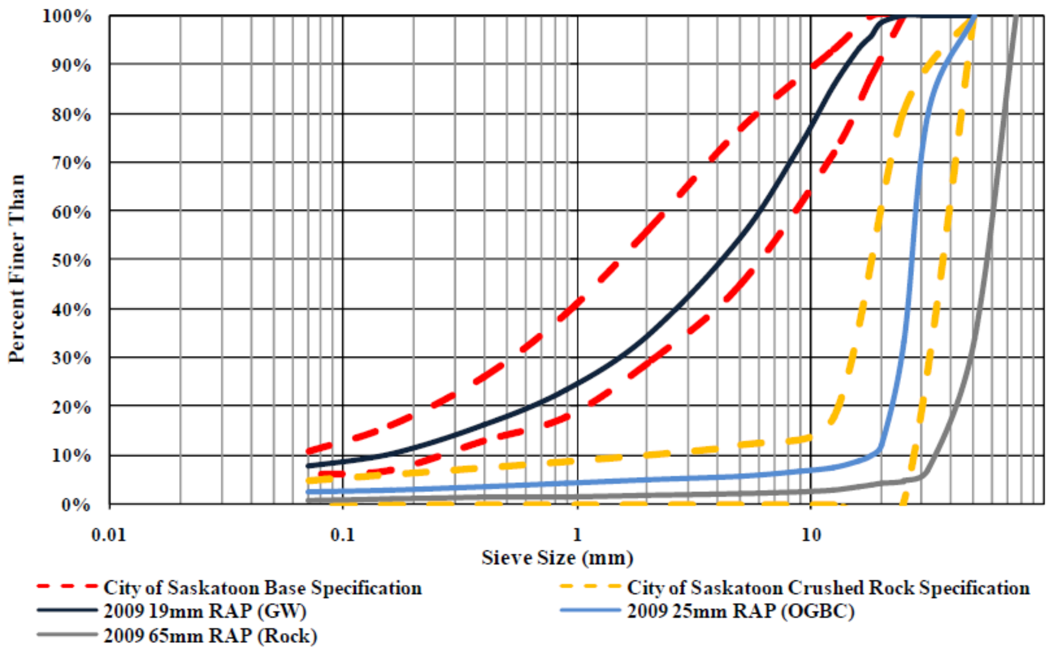

Figure 3: Crushed Hot Mix Asphalt Cement (HMAC) Grain Size Distribution