Development of a Mortar Abrasion Test for Fine Aggregates and Wear Resistance of Concrete Pavements

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Paper prepared for presentation at the
Innovation in Pavement Management, Engineering and Technologies- Design Application Session
of the 2016 Conference of the
Transportation Association of Canada,
Toronto, ON

Abstract

The cost-effective design of a rigid pavement with exposed Portland cement concrete (PCC) must take into consideration the on-going life cycle costs of maintaining adequate macrotexture and microtexture characteristics, which are essential in providing surface friction. The longevity and durability of the pavement's surface texture depends on the ability of the selected aggregates to resist polishing and of the total mix to resist abrasion. In PCC pavements, the composition and characteristics of the fine aggregate are a key component in controlling its ability to resist polishing and retain good microtexture. Macrotexture is imparted during construction, e.g., tining, dragging, or through scheduled maintenance, e.g., grinding and grooving. Macrotexture retention in PCC pavements will depend on a number of factors including aggregate type, mix design, and workmanship, e.g., depth of tining, curing.

Currently, there is insufficient development of an adequate test to directly measure the abrasion resistance of concrete as a function of the fine aggregate component and the retention of macrotexture which are directly related to the frictional performance of concrete pavements. Aggregate tests such as acid Insoluble Residue (IR) that evaluates carbonate mineral content and micro-Deval abrasion (MDA) that measures relative durability of fine aggregates are indirectly related to microtexture and macrotexture retention in concrete materials.

This paper presents the development and results of a testing program utilizing equipment originally designed for measuring the Aggregate Abrasion Value (AAV) of coarse aggregates according to British Standards BN ES 1097-8. Mortar coupons were tested on a mechanical wheel lap rotating at 30 revolutions per minute for a total of 500 revolutions while a dry abrasive charge was fed onto the lap at a rate of 800 g per minute in front of each specimen. The average mass loss of four specimens is reported as the mortar abrasion value (MAV). A total of thirty concrete fine aggregates from sources across Ontario were evaluated.

The abrasion loss for each fine aggregate mortar mix was determined at the ages of 7 and 28 days. Results were compared with the compressive strength, insoluble residue, micro-Deval abrasion loss and mineralogy of the aggregates. The determination of the mortar's resistance to abrasion was dependent on the degree of hydration and bond strength of the cement as demonstrated in comparing 7 day vs 28 day test results. Test results show that sensitivity to abrasion was minimized due to the selected water:cement ratio of the mortar. As a result, with increased curing time, variation in MAV test values was reduced with respect to aggregates of different mineral hardness. Test results show that there was little correlation established between the MAV and the various other parameters tested.

1.0 Introduction

In the early 1970's, major highways in southern Ontario were paved with asphalt using trap rock aggregate, or with Portland Cement Concrete (PCC) using locally available carbonate aggregates (Rogers et al., 2003). Currently, only a small fraction of Ontario's provincial highways consist of PCC or composite PCC and these are mainly located in southern Ontario where traffic densities are the greatest. In comparison to flexible asphalt pavements, rigid pavements can be more expensive to construct but they can offer better load distribution and durability and can provide cost-effective solutions where the benefit of a longer lifespan can add value to the life cycle costs. However, the cost-effective design of a rigid pavement with an exposed PCC surface must take into consideration the on-going maintenance, including retention of adequate surface textural characteristics, which is essential in providing good pavement friction.

The longevity and durability of a pavement's surface texture is dependent, among other things, on the composition of the materials used in its construction. Aggregates comprise a significant part of a pavement and can exert a strong influence over the texture and frictional properties of the road surface. In flexible pavements, aggregates occupy about 90% of the mix volume. Aggregates in PCC pavements, which only constitute about 2/3 of the mix by volume, play a lesser role in determining overall surface friction. In either case, maintaining texture is dependent on the ability of the exposed aggregates to resist polishing and of the total mix to resist abrasion.

Fine aggregate shape indirectly influences the frictional properties of a PCC pavement at the microtexture level, through the bonding mechanism of the aggregate and the cement paste (Whitney et al., 2013). Fine aggregate with an angular shape and rough surface texture provides better mechanical interlocking of the aggregate and cement paste, increasing the toughness of the matrix and leading to a harsh surface microtexture. In contrast, fine aggregate with a more rounded and spherical shape along with smooth surface texture tends to have a lower toughness of the matrix which encourages surface microtexture to wear and polish.

Abrasion is a result of the wearing action of vehicle tires due to the heavy loads of trucks and automobiles. Contact of a vehicle's tire with the surface of a PCC pavement leads to a shear effect (Bakke, 2006). Abrasion resistance of PCC pavements is mainly influenced by the physical and chemical properties of the fine aggregate such as shape and mineralogy (Franklin and Calder, 1974). Causes of low abrasion resistance in PCC pavement may be attributed to:

1. Soft aggregates (Mohs hardness <4)
2. Inadequate concrete compressive strength
3. Improper curing and finishing
4. Over manipulation during finishing

Although coarse aggregate may comprise more than 50% of a concrete mix, its degree of exposure at the pavement's surface is limited so it has very little influence on the surface frictional properties. The higher exposure of fine aggregate in a PCC pavement has greater significance in determining a PCC pavement's skid resistance as observed through Figure 1.

The ability of an aggregate to resist abrasion is determined by the hardness of the individual mineral grains and the strength of the bond between them. For example, quartz sandstone with a Mohs hardness of 7 has excellent resistance to abrasion, but only if the individual grains are well bonded

together (usually with calcite or dolomite cement). Poorly cemented, friable sandstones have low resistance to abrasion and are unsuitable, despite the hardness of the individual grains.

The Ministry of Transportation Ontario (MTO) uses the micro-Deval abrasion test (MDA), MTO-LS-619 to evaluate fine aggregates for use in hot mix asphalt (HMA) or PCC. In this test, aggregate particles (passing 4.75mm sieve, retained 1.18 mm) are placed in a grinding mill along with water and a steel ball charge. The loss of particles passing the 1.18mm sieve after the test is a measure of the aggregates resistance to abrasion. Previous studies have shown that this test correlates well with long term aggregate durability (Rogers et al, 2003; Rogers et al, 1991). Further research by the Texas Department of Transportation (TxDOT) indicates that aggregate particles are crushed during the abrasion process due to their small grain size distribution (Whitney et al, 2013). TxDOT modified the MDA test for abrasion resistance of PCC pavements by using mortar "brownies" made with the fine aggregate, assuming that the larger mortar size would allow the aggregate to be abraded rather than crushed. Although the test measured the abrasion resistance of the PCC mortar, it did not correlate well with the laboratory or field frictional performance of the PCC pavement.

Carbonate minerals, e.g., calcite, are relatively soft (Mohs hardness of 3) compared to most silicate rock forming minerals, e.g., feldspar, quartz (Mohs hardness of 6 - 7). Studies have also shown that aggregate with higher carbonate content results in lower abrasion and polishing resistance in comparison to high strength silicate content aggregates (Whitney et al, 2013; Bakke, 2006; Rogers et al., 2003).

The presence and amount of carbonate minerals in rocks and aggregates may be determined by acid digestion. On the other hand, siliceous rocks and minerals are inert to the effects of HCl. The insoluble residual (IR) test (MTO LS-613) is used as a means of assessing the amount of carbonate minerals (and inversely, the amount of non-carbonate, predominantly silicate minerals) in an aggregate sample. The test results are reported either as the total insoluble residue (IR_T) or the fraction of insoluble residue retained on the 75 um sieve (IR_{R75}). Although the IR test is a good indication of the carbonate/silicate mineralogy of aggregates, it does not define the abrasion resistance of the total PCC mixture.

This paper presents the development and results of a testing program to determine whether the Aggregate Abrasion Value (AAV) test (British Standard EN1097-8 2009) could be adapted to determine abrasion resistance of concrete mortar. This AAV equipment (Figure 2) resides in MTO's materials laboratory and is routinely used to evaluate the ability of coarse aggregate to retain macrotexture in HMA surface friction courses (Rogers et al, 2003).

2.0 Material

Fine aggregate samples were obtained from stockpiles of processed concrete sands that are commercially available for use in PCC pavements. The sources were selected from four of MTO's administrative regions - West, Central, Eastern and Northeastern regions and represent potential suppliers of materials for PCC pavements. Some sources within similar geographical locations and mineralogical content were excluded to avoid duplication. Locations of the sources sampled for this project are shown in Figure 3. A summary of the samples examined in this report is included in Table 1.

A total of 30 different concrete sands obtained from various commercial aggregate sources in Ontario were examined. Each of the sources are listed on MTO's Concrete Aggregate Sources List, which identifies aggregate products for use in PCC that have been prequalified against MTO's alkali aggregate reactivity requirements. This list is made available to contractors for bidding purposes on ministry

contracts. Sources were chosen to represent a wide geographical area and range of mineralogical content.

3.0 Testing

The AAV test exposes aggregates to grinding by direct shear on a large mechanical lap wheel with abrasive sand (Figure 2). The lap rotates at 30 revolutions per minute for a total of 500 revolutions while the dry abrasive charge is fed onto the lap in front of each specimen. The index used to evaluate abrasion, the AAV, is the average mass loss of two specimens in grams, when measured before and after the test, multiplied by the volume of the aggregate and divided by the aggregate's relative density.

Specimens for the AAV test normally consist of an aggregate coupon in which selected coarse aggregate particles are cast with a hardened epoxy base to hold the individual particles in place. For this research, the aggregate coupons were replaced with mortar coupons and tested in the same manner. In this case, the average mass loss of four mortar coupons was evaluated and is referred to as the Mortar Abrasion Value, (MAV). The abrasion loss for each fine aggregate mortar mix was determined at the ages of 7 days (MAV_7) and 28 days (MAV_{28}). Additionally, mortar cubes were cast using the same materials and tested for 7 and 28 day compressive strength (ASTM C109).

Each of the aggregates used in this investigation was also tested for an evaluation of their physical properties and mineral composition. These tests included Absorption and Relative Density (MTO LS-604/LS-605), Insoluble Residue (MTO LS-613), Petrographic Analysis (LS-616), Micro-Deval Abrasion (MTO LS-619) and Uncompacted Void Content (MTO LS-629/AASHTO T304). A summary of physical and chemical properties and petrographic analysis of the aggregates are tabulated in Table 2 and

Table 3 respectively.

3.1 Mortar Mix Design

The cement mortar mix used for this investigation was adopted from the requirements of the MTO Method of Test for Accelerated Detection of Potential Deleterious Alkali-Silica Reactive Aggregate by Expansion of Mortar Bars, MTO LS-620, which used a water to cement ratio of 0.44 and fineness modulus of 2.9. The cement used for the mortar mixes for preparation of coupons and cubes was general use (GU) Type 10 cement provided by St Marys Cement. The chemical and physical properties of the cement are given in Table 4.

The total proportion of fine aggregate with respect to the cement was selected as 2.25:1 by mass. For each aggregate, mortar was prepared so that the total quantities of the mix design ingredients were sufficient to cast eight mortar coupons for MAV testing and 6 mortar cubes for compressive strength tests. The design quantities for each mix are given in Table 5.

3.2 Mixing, Casting and Curing of Mortar Coupons

Mortar coupons were prepared using the same molds used for the AAV test procedure (
Figure 4). Mold dimensions are 92±0.1 mm in length, 54±0.1 mm in width and 16±0.1 mm in depth. After the first casting trial, the depth of the specimen was reduced to 15±0.1 mm to diminish the breakage of the mortar coupons during the demolding process due to restraining of the coupon along the outer wall. Cube specimens were prepared by standard molds specified as per ASTM C109.

The mixing procedure was completed according to ASTM C305 (Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency). Each cement mortar coupon and compressive strength cube was cast into its respective mold in two lifts (Figure 5). Each lift was compacted 36 times using a rubber tamping rod. After casting, any excess mortar was cleaned away and the surface was finished using a trowel.

The coupons and cube specimens were then placed in a moisture room for 24 ± 2 hours at 99.9% humidity for curing after which all specimens (coupons and cubes) were demolded. The cast specimens were then placed in a saturated lime water solution to prevent leaching of calcium. Half of the specimens were removed after 7 days for testing. The remaining specimens were removed and tested after 28 days. This process was repeated for all 30 aggregate samples. In total, 180 cubes were cast for strength testing and 240 coupons were cast for abrasion testing.

3.3 MAV Testing

After removal from the curing room and the lime solution, each specimen was surface dried using a towel to ensure that mass loss as a result of surface water was not included in the MAV. Prior to testing on the abrasion apparatus, the initial weight of each coupon was measured. Two specimens were tested on the equipment simultaneously. To ensure there was no movement and adequate contact pressure of the coupon with the rotating lap, a weight was placed centrally on top of each specimen. The total weight of the coupon and weight sample was 2kg± 10g. The smooth formed surfaces of the coupons were placed on the 600mm diameter steel lap on the abrasion machine as per Figure 6. The abrasive material is Ottawa silica sand which is fed onto the lap from a hopper in front of each coupon. The abrasive feed was constantly monitored during the test for even distribution. After testing, the final

mass was recorded. The average mass loss of four specimens for each aggregate was reported as the MAV.

4.0 Results and Discussion

4.1 MAV Results

The MAV results were calculated based on the average mass loss of 4 coupons instead of using average volumetric loss of 2 coupons per BS EN1097-8 2009. This modification improved the sensitivity of the data. As per the test standard, outlier results were eliminated from the calculation if the average abrasion mass loss differed by more than 0.2g from each specific coupon within the set of four. The average 7 and 28-day compressive strengths were calculated and reported according to ASTM C109. A summary of the compressive strength results and MAV for 7 and 28-days is presented in Table 6

Figures 7 through 10 illustrate variations in surface texture for selected specimens containing aggregate with different hardness at 7 and 28 days. Figure 7 shows the surface texture for specimen NE03 that contains 99.5% silicate mineral aggregate as determined by petrographic analysis and 94.5% IR_T. The MAV_7 specimen has a rough texture with exposed aggregates on the surface, while an evenly abraded surface was observed for the MAV_{28} coupon.

Figure 8 shows the surface texture for specimen C19, made with fine aggregate containing 98.6% carbonate mineral content and 2.9% IR_T. For this specific specimen, there is no observable surface texture variation between the tested coupons for 7 day and 28 day curing. Both coupons have a very smooth surface texture with evenly abraded surface.

Figure 9 shows the surface texture for specimen C06 made with a fine aggregate of intermediate silicate and carbonate mineral content (LS-616 silicate =50.7%, IR_T = 48.7%). For this material there is a small difference in terms of MAV_7 and MAV_{28} surface texture. Both specimens are abraded evenly but the MAV_7 coupon has a slightly rougher texture with respect to MAV_{28}.

Figure 10 shows abraded coupons made with fine aggregate that consists of 89.1% silicate mineral, including 10.9% mica (IR_T = 95.8%). The MAV_7 specimen exhibits a rough surface texture with visible abrasion of some of the coarser aggregates. The MAV_{28} coupon made with the same material shows a more evenly abraded surface texture, with fewer coarser aggregates being abraded.

4.2 Compressive Strength

Figure 11 plots the MAV against the average compressive strength of 3 cubes for each mortar mix at age 7 days and 28 days curing. The 7 day compressive strength ranged from 38.7MPa to 54.7MPa and the 28 day compressive strength ranged from 47.5 MPa to 66.4 MPa (Table 6, Table 7). In general, higher compressive strengths resulted in lower MAV mass loss, although both 7 day and 28 day strengths show little correlation with MAV test results. However, both data sets illustrate similar patterns. On average, 28 day curing resulted in lower MAV mass losses, which is assumed to be a result of improved bond development due to prolonged cement hydration. Figure 11 also illustrates that compressive strength variation for both 7 and 28 days are significant even though the same W:C ratio, fineness modulus and same casting and curing regime were used for all mixes.

Table 7 includes a summary of compressive strength and MAV test results. Average compressive strengths between samples tested at 7 day and 28 day curing increased by 20.4%, while the range increased by 18.1 %. Average MAV test results between samples tested at 7 day and 28 day curing decreased by 9.6%, while the range decreased by 20.0%.

Figure 12 shows the probability of occurrence for MAV losses at 7 and 28 days calculated using the NORM distribution function of Microsoft Excel. For each data set of MAV_7 and MAV_{28}, the individual MAV data point and the statistical mean and standard deviation(s) were used to generate the probability of occurrence for each designated MAV mass loss. The function determines the probability of each of the MAV losses with respect to the mean loss of the data set.

The probability of occurrence around the mean value for MAV_7 and MAV_{28} results are 35% and 50% respectively. This indicates a 35% chance of any single MAV_7 test result being close to the mean value of the data set (11.55g) whereas there is a 50% probability for a MAV_{28} test result being close to the mean value of the 28 day data set (10.54 g). The higher probability for MAV_{28} test data demonstrates a lower mass loss, and subsequent higher resistance to abrasion with increasing age and curing time.

4.3 IR and Petrographic Analysis

The IR test is the indirect measurement of the carbonate mineral aggregate content. The IR_T value reports the total residue left behind after digestion with HCl while the $IR_{R.75}$ test results only include the residue retained on the 75µm sieve after washing. Material passing the 75µm sieve is silt and clay sized particles, which may be comprised of a significant amount of silicate clays minerals. In limestones and dolostones, these clay minerals are often present as argillaceous content (shale). Difference in IR_T and $IR_{R.75}$ may be used as an estimate of the clay component of carbonate rocks.

Figure 13 is a comparison of the carbonate content determined by Petrographic Analysis and by the insoluble residue test. Both of these tests correlate well with each other. A better correlation is demonstrated between the $IR_{R.75}$ results and carbonate minerals determined by LS-616 since both of these tests examine the retained 75µm fraction only.

Comparing IR and MAV test results, Figure14 shows that with increasing IR_T and IR_{R75}, there is a general decrease in MAV_7 and MAV_{28} losses, even though the coefficient of correlation R^2 is low. It is noted that MAV_7 results show a slightly improved correlation with respect to both IR_T and $IR_{R.75}$ results in comparison with MAV_{28}. Consequently, the MAV_7 results were used for further analysis of IR data.

The R^2 coefficient for $IR_{R.75}$ results with respect to MAV_7 was improved by 34% in comparison with IR_T results (Figure14b), demonstrating a better relationship between MAV_7 and IR. The low correlation between MAV and IR results for the data range in this investigation could be attributed to aggregate properties that influence the MAV results while having less impact on IR results. One of these properties is the presence of mica, which is a common silicate mineral with a Mohs hardness of 2.5 and is almost exclusively found in igneous and metamorphic rock types. Due to its soft nature, it is not commonly found as a clastic component of sedimentary rocks.

Mica is insoluble in HCl so that its presence increases IR test values. Figure 15(a) demonstrates that with increasing mica content, as determined through petrographic analysis, $IR_{R.75}$ also increases. Typically, where the mica content is greater than 3%, IR_{R75} values are greater than 70%. Figure 15(b) shows that

with increasing mica content, the MAV_7 generally increases, demonstrating the influence that mica has on decreasing abrasion resistance.

The effect of mica may be noted from examination of samples C14, NE01, NE02 and NEO3, all of which had IR contents greater than 90% and with mica contents of 4.2%, 5.0%, 10.9% and 0.5% and MAV_7 test results of 11.35, 11.10, 13.71 and 9.90 respectively (Table 2,

Table 3 and Table 6). Figure 16 shows a strong relationship between mica content and MAV for these samples. Specimens containing high mica contents can be expected to have both high MAV mass loss and high IR values.

A plot illustrating R^2 coefficient (Figure17a) for $IR_{R.75}$ and MAV_7 results with mica content suggests the strongest correlations with mica content values of less than or equal to 3% for the set of data used in this investigation. A plot of samples meeting this criteria for MAV_7 and $IR_{R.75}$ in Figure17b shows the correlation to be much stronger than that shown in Figure14. High MAV results indicate low resistance to abrasion while low $IR_{R.75}$ indicate the predominance of soft carbonate rock and mineral types.

4.4 MDA and Petrographic Analysis

Figure 18 shows MDA loss vs MAV test results. Both 7 day and 28 day values do not show any significant correlation with MDA, although the MAV_7 loss has a slightly improved relationship in comparison to MAV_{28}. This indicates these two tests are fundamentally different in how abrasion loss is simulated. The MDA test produces abrasion by tumbling motion within a rotating jar while the MVA test abrades the test specimen by shear attrition. In addition, the MDA test acts upon only the aggregate and not the mortar.

The abrasion loss in terms of both MDA and MAV depends on aggregate's hardness and strength. Figure 19 shows that as the silicate content (determined by petrographic analysis, LS-616) increases, the MDA and MAV_7 losses decrease for the data range in this investigation, although MDA has a significantly higher correlation R^2 than MAV_7 with respect to silicate mineral content.

Absorption has a noticeable influence on test results as measured by the MDA test, but less so with the AAV test equipment (Figure 20) - the correlation between absorption and MDA is much stronger. One of the differences between these two tests is that the aggregates in the MDA test are unbound in a saturated environment whereas the MAV test is conducted in dry conditions on bound particles. This leads to higher abrasion loss in the MDA test due to interparticle action as well as the abrasive charge. Absorption values of the aggregates tested do not cover a large range; however, they are all within MTO specifications for this physical property.

4.5 Relative Density

Figure 21 shows the relationship between average bulk relative density and MAV. Both MAV_7 and MAV_{28} values increase with increasing bulk relative density of aggregates with R^2 values of 0.2227 and 0.2761 respectively. It should be noted that denser aggregates would result in higher mass loss for the same volume of material abraded.

5.0 Summary

The work discussed in this paper was conducted over a relatively short period of time from late fall to late spring. A total of 30 aggregate samples of concrete sands were collected across a large region of the province and were subject to standard test methods including gradation, absorption, relative density, micro-Deval abrasion, insoluble residue and petrographic analysis. In addition, 180 mortar cubes and 240 mortar coupons were cast for each aggregate and cured for 7 days and 28 days after which they were subject to compressive strength testing and experimental MAV testing. All of this required careful planning and coordination. The work is considered preliminary.

The following may be drawn from these investigations:

- The MAV test examined the response to abrasion of a total mortar mix using a modification of existing equipment used by MTO to measure the abrasion resistance of coarse aggregates in hot mix asphalt (AAV).

- The mortar mix design provided a low w:c ratio which led to relatively high compressive strength measurements of the cured specimens. High compressive strengths represent a strong frictional bonding between the aggregate and the cement paste, which may have led to the small range of abrasion loss for the various aggregate types. With increased curing time the abrasion loss measurement loses its sensitivity with respect to the aggregate's hardness and becomes more dependent on the performance and bonding development of the cement paste. This was demonstrated through the reduction of MAV loss, lower mass loss variation with respect to different aggregate's hardness and uniformly abraded surface loss for 28 days specimens.

- Abrasion of the mortars in the AAV apparatus reflected properties of both the mineral and the cement paste. Abrasion resistance as a function of the individual aggregate properties was not measured directly.

- Insoluble residue testing reflects the varying content of relatively soft, carbonate and relatively harder siliceous minerals. Increases in carbonate minerals generally resulted in an increase in MAV test results indicating a lower resistance to abrasion.

- The presence of micaceous minerals was identified as being significant in determining resistance to abrasion of the cement mortars. Aggregates containing high mica content showed low resistance to abrasion. Aggregates with less than 3% mica content led to an increase in correlation between the MAV and IR results.

- No relationship was demonstrated between the MDA test, which measures abrasion of a wet aggregate, and the MAV test, which measures abrasion of a mortar with the same aggregate. In general, increasing silicate mineral content resulted in higher resistance to abrasion. However, MAV was less sensitive to this parameter.

- There was no significant relationship between MAV losses and an aggregate's absorption capacity.

- Test results from this project identify the positive effect of proper curing on abrasion resistance of mortars. Proper curing of field concretes will have similar positive effects on the abrasion resistance of PCC pavements.

6.0 Future Directions

The development of an effective abrasion test for mortar specimens is still under investigation and requires further study. In particular, the high bond strength of the mortar did not significantly differentiate the abrasion effect on soft versus hard mineral aggregates. Reducing the curing time would effectively reduce the overall cement hydration, and corresponding bond strength, as well as allow for quicker return of the test data. Modification to the water:cement ratio could also be investigated as a

means of reducing bond strength effects. In addition, all the selected aggregates in this study satisfied MTO specification requirements for MDA results for concrete pavement. Variability in MDA resistance to abrasion of alternative materials outside the acceptance limits could also be investigated in order to gain a more effective evaluation of microtexture retention and frictional performance of PCC pavements.

Acknowledgements

The authors gratefully acknowledge the aggregate producers for supplying materials for this project. We would also like to thank and appreciate the staff of MTO's Material Engineering and Research Office who conducted sampling and additional laboratory testing towards the completion of this report, specifically: Peter Byer, Mahabir Singh, Edmond Wong, Ram Kandel, Julia Gabriele and Richard Sideritz.

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Tables:

Table 1. Fine Aggregate Sample Summary

Sample	MTO Sample Number	Deposit Type	Geological Setting
W01	101 (A)	Pit	Ice Contact
W05	105 (A)	Pit	Outwash
W06	106 (A)	Pit	Outwash
W09	109 (A)	Pit	Beach
C01	201 (A)	Pit	Outwash
C02	202 (A)	Pit	Outwash
C03	203 (A)	Pit	Outwash
C04	204 (A)	Pit	Ice Contact
C05	205 (A)	Pit	Ice Contact
C06	206 (A)	Pit	Ice Contact
C07	207 (A)	Pit	Outwash Terrace
C08	208 (A)	Pit	Outwash
C09	209 (A)	Pit	Ice Contact
C11	211 (A)	Pit	Outwash
C12	212 (A)	Pit	Outwash
C13	213 (A)	Pit	Ice Contact
C14	214 (A)	Quarry	Quarry
C15	215 (A)	Pit	Outwash
C16	216 (A)	Pit	Outwash
C17	217 (A)	Pit	Outwash
C19	219 (A)	Quarry	Quarry
E01	301 (A)	Pit	Outwash/Ice Contact
E02	302 (A)	Pit	Beach
E05	305 (A)	Pit	Beach
E06	306 (A)	Pit	Beach
E07	307 (A)	Pit	Beach
E10	310 (A)	Pit	Outwash
NE01	401 (A)	Pit	Ice Contact
NE02	402 (A)	Quarry	Quarry
NE03	403 (A)	Pit	Delta

Table 2. Fine Aggregate Physical and Chemical Properties

Sample	Insoluble Residue MTO LS-613		MDA Loss (%) MTO LS-619	Absorption (%) MTO LS-605	Relative Density LS-605	Uncompacted Void Content (%) LS 628
	IR_T (%)	$IR_{R.75}$ (%)				
W01	54.7	33.0	11.7	0.99	2.715	43.4
W05	18.9	16.0	13.2	1.06	2.733	41.6
W06	31.9	27.6	13.1	1.48	2.636	41.4
W09	61.7	58.1	11.1	1.45	2.602	40.1
C01	61.9	57.8	8.5	0.67	2.664	40.2
C02	57.4	51.3	12.5	1.33	2.623	41.4
C03	36.7	50.6	15.5	0.82	2.668	41.1
C04	47.5	43.4	8.4	0.45	2.685	39.9
C05	48.3	43.5	8.9	0.40	2.693	40.9
C06	48.1	44.8	9.4	0.56	2.675	40.6
C07	40.3	36.2	15.0	1.35	2.665	42.8
C08	57.0	52.0	9.6	*	*	*

C09	49.3	46.9	8.6	0.59	2.686	41.7
C11	47.2	44.2	9.4	0.58	2.676	40.1
C12	51.1	45.0	11.5	1.00	2.751	44.1
C13	73.3	67.9	15.8	1.88	2.682	45.1
C14	92.6	91.5	6.7	0.31	2.726	47.9
C15	39.7	34.5	12.9	1.07	2.692	41.7
C16	24.5	18.0	11.3	1.02	2.718	41.7
C17	42.3	36.5	10.6	1.23	2.676	42.3
C19	2.9	0.0	15.4	1.36	2.748	47.2
E01	38.5	33.8	14.2	0.87	2.664	41.8
E02	46.0	41.1	8.5	0.55	2.682	40.3
E05	64.9	59.4	14.4	0.71	2.697	31.4
E06	73.7	70.9	10.9	0.98	2.657	42.8
E07	68.8	62.0	14.5	0.92	2.680	42.2
E10	65.7	59.1	11.8	0.81	2.663	43.3
NE01	96.6	95.4	4.6	0.37	2.711	43.4
NE02	95.8	93.5	6.1	0.49	2.790	51.2
NE03	94.5	92.1	4.0	0.46	2.697	41.0

*Insufficient material for testing.

Table 3. Petrographic Examination Results (MTO LS-616)

Sample	Silicates	Carbonates	Shale, Argillite, Clay, Ochre	Micas	Chert	Cemented Particles	Sulphates	Sulphides
W01	27.0	67.1	0.0	0.5	5.4	0.0	0.0	0.0
W05	26.4	73.4	0.0	0.1	0.1	0.0	0.0	0.0
W06	31.0	68.3	0.0	0.2	0.5	0.0	0.0	0.0
W09	50.3	46.1	0.0	0.3	3.1	0.0	0.0	0.2
C01	56.3	41.9	0.0	0.5	0.0	1.3	0.0	0.0
C02	40.9	55.2	0.0	0.2	0.0	3.7	0.0	0.0
C03	53.6	45.3	0.0	0.4	0.0	0.7	0.0	0.0
C04	45.3	54.1	0.0	0.6	0.0	0.0	0.0	0.0
C05	41.2	58.3	0.0	0.4	0.1	0.0	0.0	0.0
C06	50.7	47.8	0.0	1.2	0.3	0.0	0.0	0.0
C07	38.3	59.8	0.0	0.4	0.3	1.2	0.0	0.0
C08	49.6	46.3	0.0	1.3	0.6	2.1	0.0	0.0
C09	52.2	45.8	0.0	1.3	0.0	0.7	0.0	0.0
C11	43.8	55.7	0.0	0.5	0.0	0.0	0.0	0.0
C12	37.4	60.6	0.0	0.0	0.5	1.5	0.0	0.0
C13	52.8	43.0	0.1	0.0	0.5	3.6	0.0	0.0
C14	95.8	0.0	0.0	4.2	0.0	0.0	0.0	0.0
C15	41.1	57.3	0.0	0.6	0.4	0.5	0.0	0.0
C16	28.7	70.6	0.0	0.7	0.0	0.0	0.0	0.0
C17	33.6	61.7	0.0	0.6	1.3	2.8	0.0	0.0
C19	1.4	98.6	0.0	0.0	0.0	0.0	0.0	0.0
E01	38.2	61.3	0.0	0.5	0.0	0.0	0.0	0.0
E02	44.2	54.7	0.0	1.1	0.0	0.0	0.0	0.0
E05	62.8	36.2	0.0	0.9	0.0	0.1	0.0	0.0
E06	72.1	23.8	0.0	3.4	0.6	0.2	0.0	0.0
E07	53.9	43.9	0.0	1.8	0.0	0.4	0.0	0.0
E10	55.8	41.6	0.1	2.5	0.0	0.1	0.0	0.0
NE01	95.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0
NE02	89.1	0.0	0.0	10.9	0.0	0.0	0.0	0.0
NE03	99.5	0.0	0.0	0.5	0.1	0.0	0.0	0.0

Table 4. Properties of cement used for mortar mix

Composition	Value
SiO_2	19.6 (%)
Al_2O_3	4.9 (%)
Fe_2O_3	3.1 (%)
CaO	61.4 (%)
MgO	3 (%)
SO_3	3.6 (%)
Alkalis (as Na_2O)	0.7 (%)
Loss on Ignition	2.3 (%)
Specific Gravity	3.15

Table 5. Design Quantities of Individual Mortar Mixes for Test Specimens

Material		*Mass (g)	Cumulative % Retained
Aggregate (Sieve Size, retained)	2.36 mm	269.2	10
	1.18 mm	673.0	35
	600 µm	673.0	60

	300 µm	673.0	85
	150 µm	403.8	100
Water		526.4	-
GU Cement		1196.4	-

Table 6. 7 and 28-day Compressive Strength and MAV (Mass Loss) results

Sample	7-Day					28-Day				
	Compressive Strength (MPa)	MAV (g)	s	Max	Min	Compressive Strength (MPa)	MAV (g)	s	Max	Min
W01	50.5	10.95	1.85	12.6	9.3	59.8	10.27	0.51	10.7	9.7
W05	48.4	12.58	1.38	13.8	10.7	57.1	11.08	1.03	12.0	9.6
W06	48.3	11.6	0.70	12.5	11.0	52.6	10.50	1.03	11.7	9.2
W09	47.7	11.75	0.97	12.7	10.5	53.1	10.08	1.70	12.5	8.8
C01	45.7	10.65	1.40	12.3	9.3	56.9	10.28	0.94	11.4	9.4
C02	43.9	10.70	1.34	12.3	9.5	61.0	9.80	0.27	10.0	9.5
C03	49.4	9.88	0.32	10.1	9.5	55.7	9.33	0.77	10.3	8.5
C04	38.7	10.08	0.34	10.4	9.6	51.9	9.68	0.81	10.4	8.6
C05	46.0	12.20	0.61	12.9	11.7	54.8	11.30	0.51	11.8	10.6
C06	46.4	12.15	0.92	12.8	9.4	55.9	10.60	0.80	11.5	9.8
C07	47.9	11.93	0.85	12.8	11.1	60.3	10.83	0.90	12.1	10.2
C08	46.1	10.90	1.14	12.6	10.2	61.5	10.10	0.62	10.6	9.2
C09	45.8	11.18	0.68	11.9	10.5	61.4	10.93	0.67	11.5	10.2
C11	42.3	10.20	0.36	10.5	9.8	60.2	9.90	0.27	10.1	9.5
C12	54.7	11.80	0.96	12.5	10.4	66.4	11.45	0.39	11.8	10.9
C13	53.4	10.24	0.82	10.9	9.4	63.9	9.76	0.92	10.5	9.1
C14	47.7	11.35	0.83	12.1	10.4	54.0	10.28	0.25	10.6	10.0
C15	49.7	12.58	0.67	13.5	11.9	55.6	9.83	0.55	10.2	9.2
C16	50.9	13.45	0.58	14.3	13.1	55.7	11.65	0.86	12.4	10.5
C17	39.7	11.53	0.92	12.7	10.7	56.1	10.33	0.82	11.3	9.3
C19	42.0	14.8	1.67	16.0	9.1	52.7	11.18	1.63	12.8	9.4
E01	42.1	11.10	0.52	11.7	10.8	52.4	10.23	0.59	10.8	9.4
E02	44.9	11.50	1.50	13.0	10.0	53.7	11.70	0.84	12.6	10.8
E05	52.7	11.70	0.53	12.4	11.2	60.9	10.67	0.67	11.1	9.9
E06	43.3	12.60	0.70	13.4	12.1	51.0	10.05	0.99	11.4	9.3
E07	48.9	11.90	0.56	12.5	11.4	52.1	10.50	0.37	10.9	10.1
E10	51.2	10.53	0.60	11.3	10.0	52.9	11.53	0.49	11.1	10.2
NE01	50.5	11.10	0.98	11.9	10.0	57.4	10.73	0.46	11.0	10.2
NE02	38.9	13.71	0.77	14.9	12.5	47.5	12.76	0.49	13.6	12.0
NE03	48.2	9.90	1.25	11.2	8.7	61.9	8.75	0.93	9.4	7.4

Table 7. Summary of MAV and Compressive Strength Tests

	7-Day		28-Day	
	Compressive Strength (MPa)	MAV (g)	Compressive Strength (MPa)	MAV (g)
Average	46.9	11.55	56.5	10.54
Max	54.7	14.80	66.4	12.76
Min	38.7	9.88	47.5	8.75
Range	16.0	4.92	18.9	4.10

Figures:

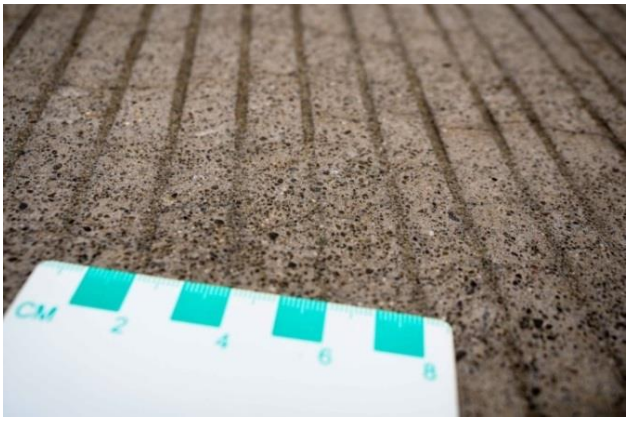


Figure 1: Exposed fine aggregate on an abraded concrete pavement surface.

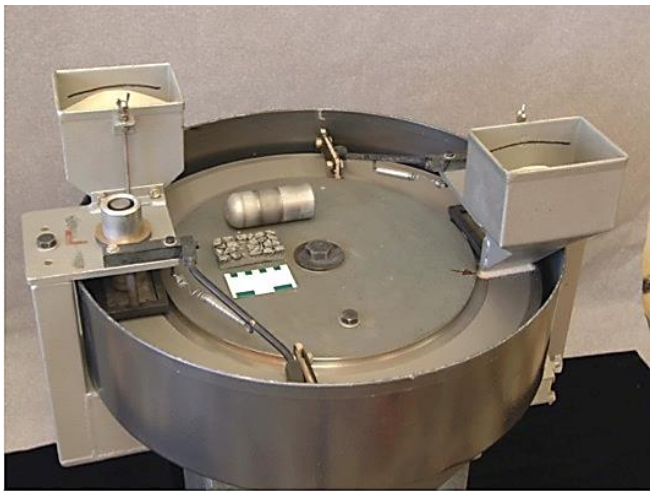


Figure 2. Aggregate Abrasion Value Test Apparatus

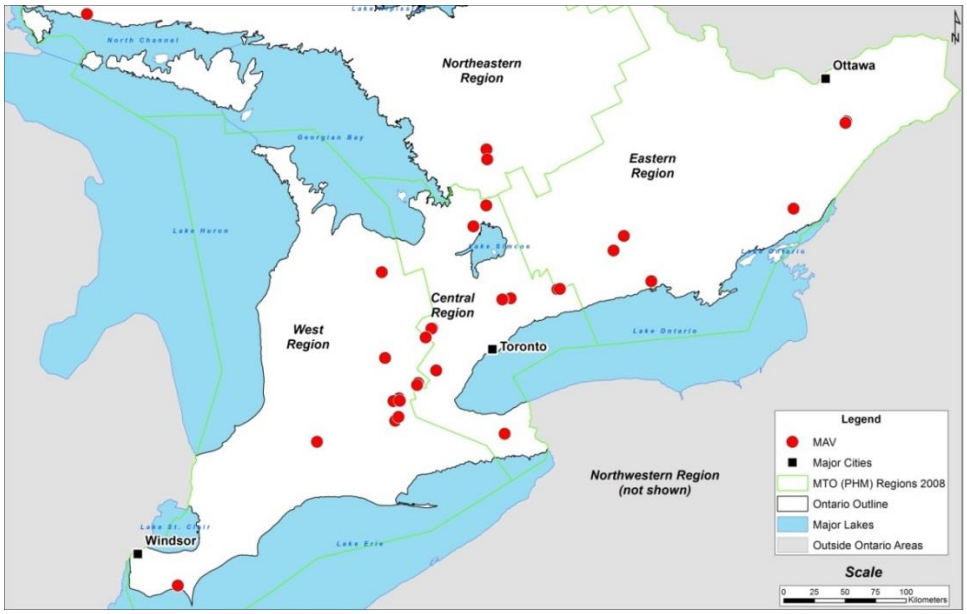


Figure 3. Sample locations of materials used in this project.

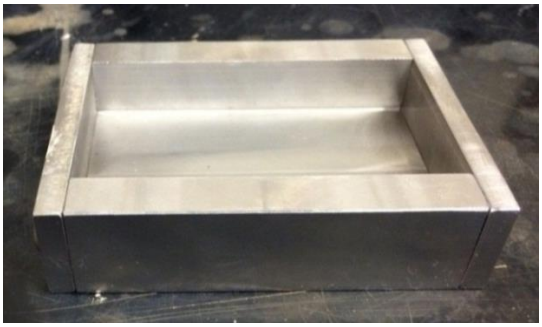


Figure 4. Mold used for casting MAV coupon

Figure 5. Casting process of a set of mortar coupons and cubes for each aggregate.

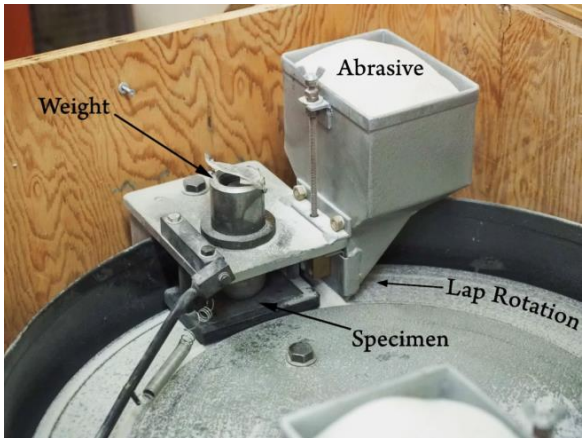


Figure 6. Abrasion testing of mortar coupon on the AAV machine.

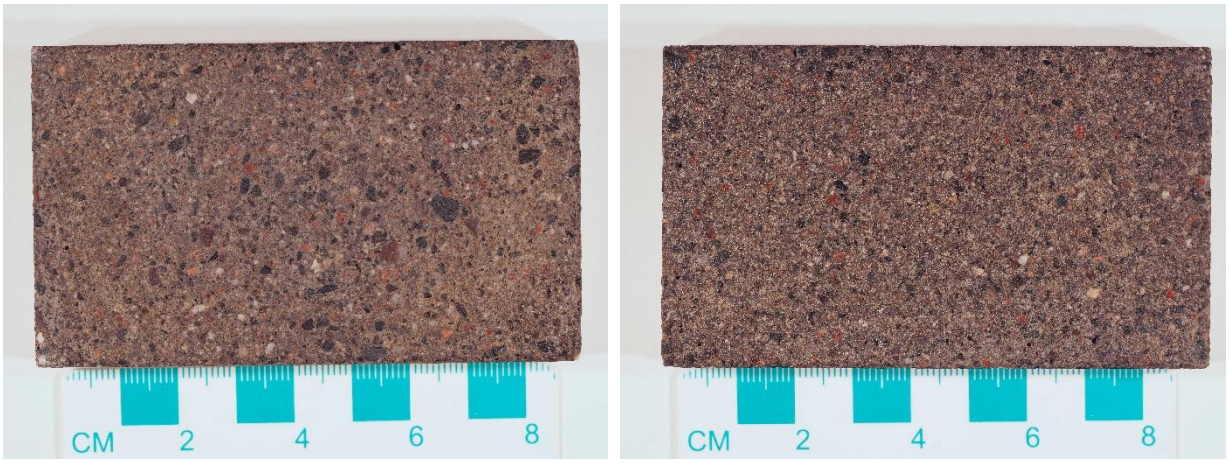


Figure 7. Sample NE03 after abrasion testing – 7-day (left) and 28 day (right)

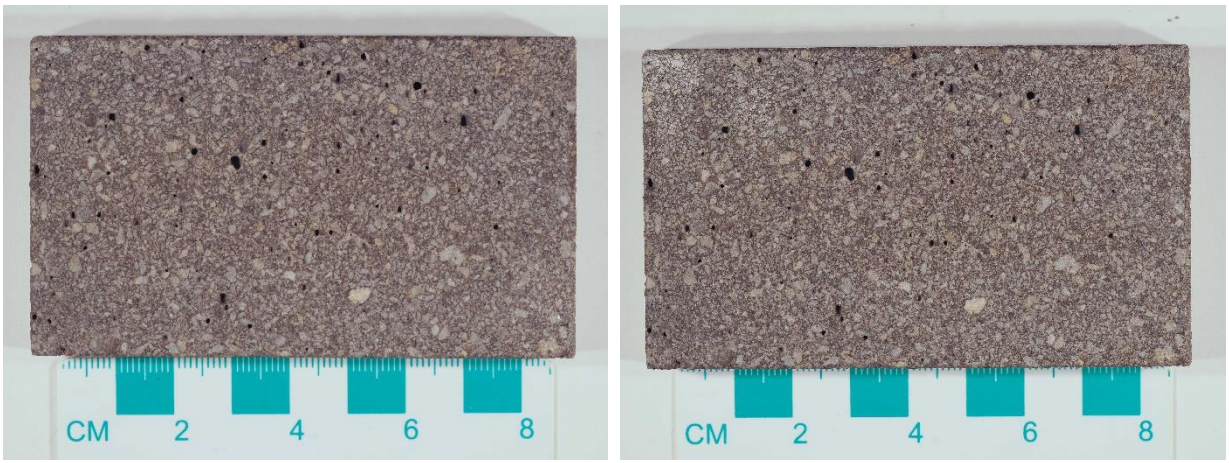


Figure 8. Sample C19 after abrasion testing – 7-day (left) and 28 day (right)

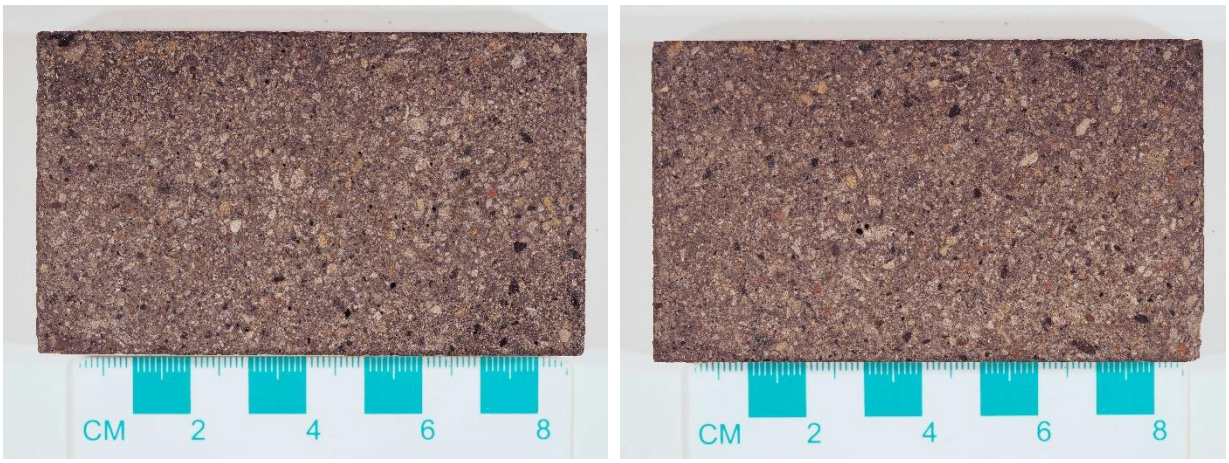


Figure 9. Sample C06 after abrasion testing – 7-day (left) and 28 day (right)

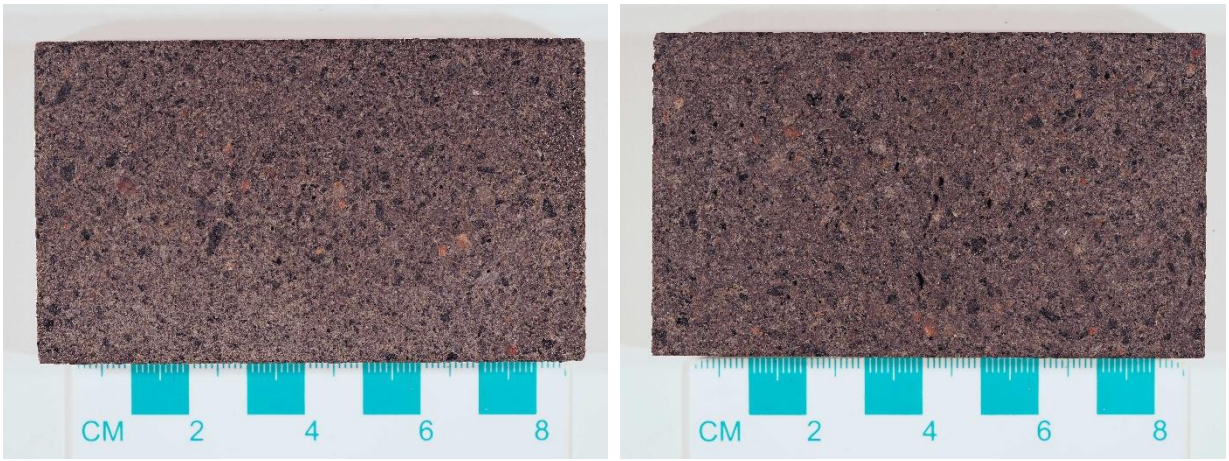


Figure 10. Sample NE02 after abrasion testing – 7-day (left) and 28 day (right)

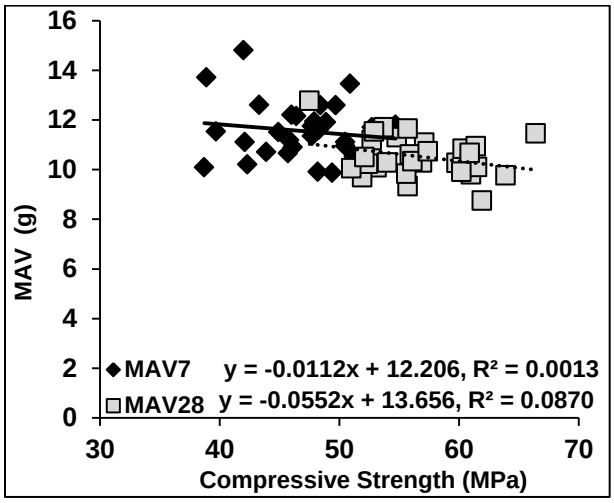


Figure 11. Relationship between compressive strength and MAV loss

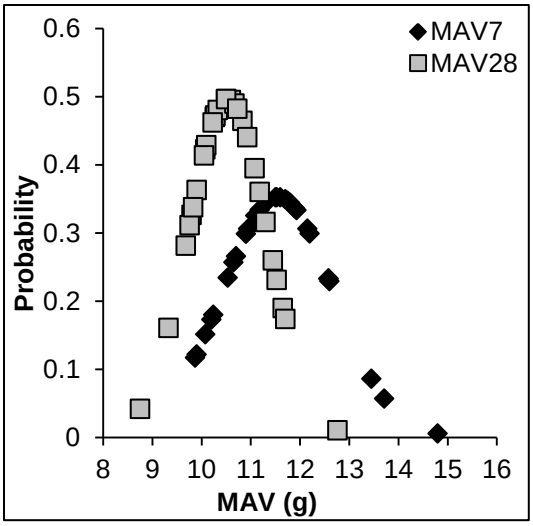


Figure 12. Probability of Occurrence for MAV Losses

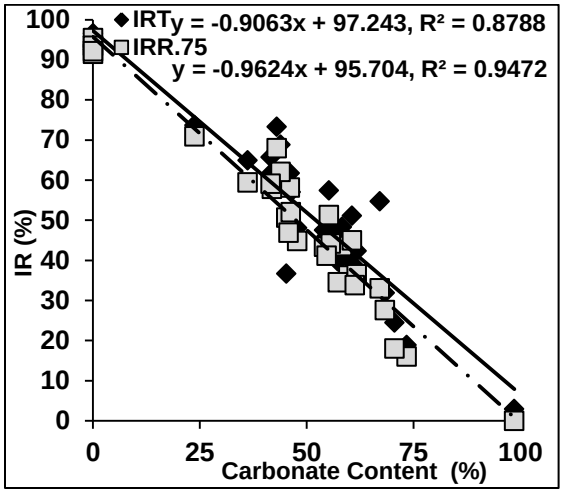
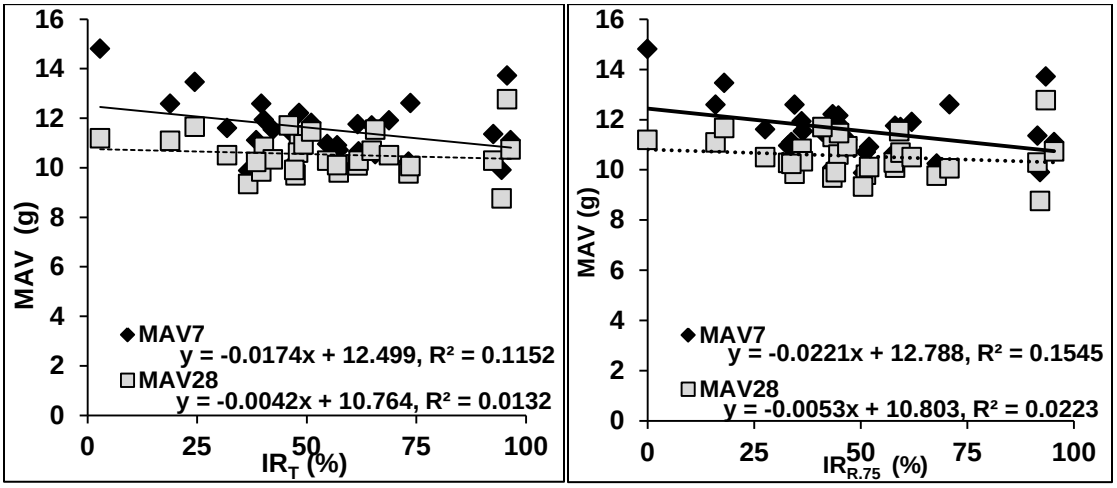
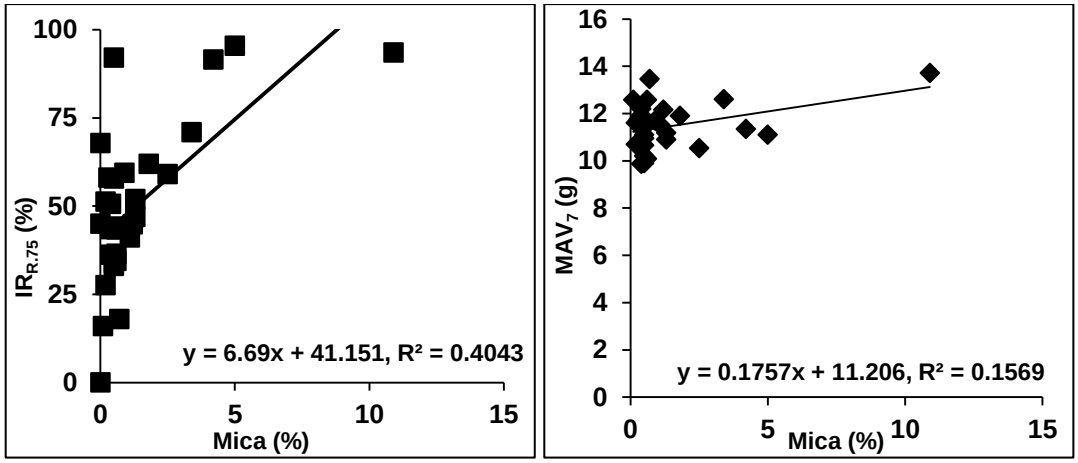


Figure 13. IR test results compared with carbonate content (Petrographic Analysis, LS-616)



(a) Total Insoluble Residue vs. MA (b) Retained 75um Insoluble Residue vs. MAV

Figure14. Relationship between IR and MAV Losses



(a) Relationship between Mica and IRR.75 (b) Relationship between Mica and MAV7

Figure 15. Influence of Mica on IR and MAV Results

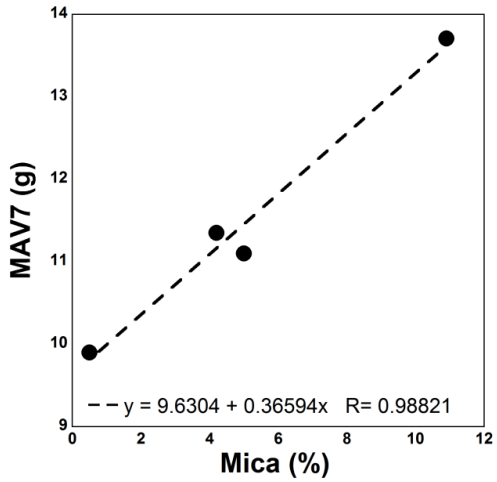
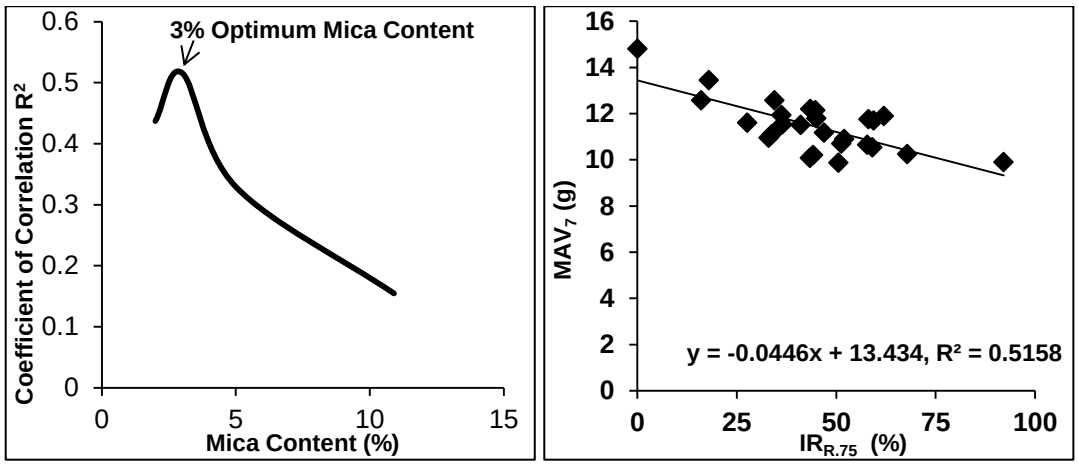


Figure 16. Relationship between MAV and mica content for samples with IR>90%



(a) Optimum mica content (b) IRR.75 and MAV for samples with <3% mica content

Figure17. Influence of mica content on MA

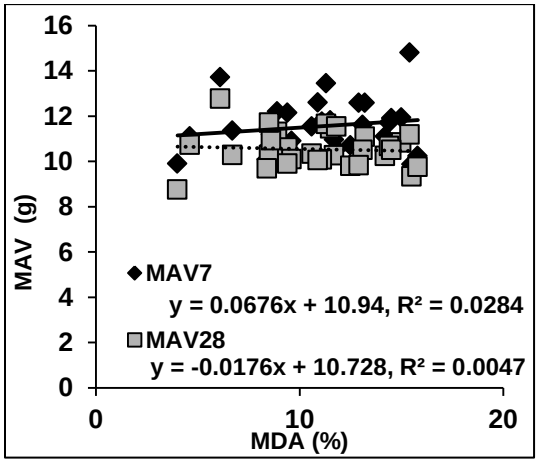


Figure 18. Relationship between MDA loss and MAV

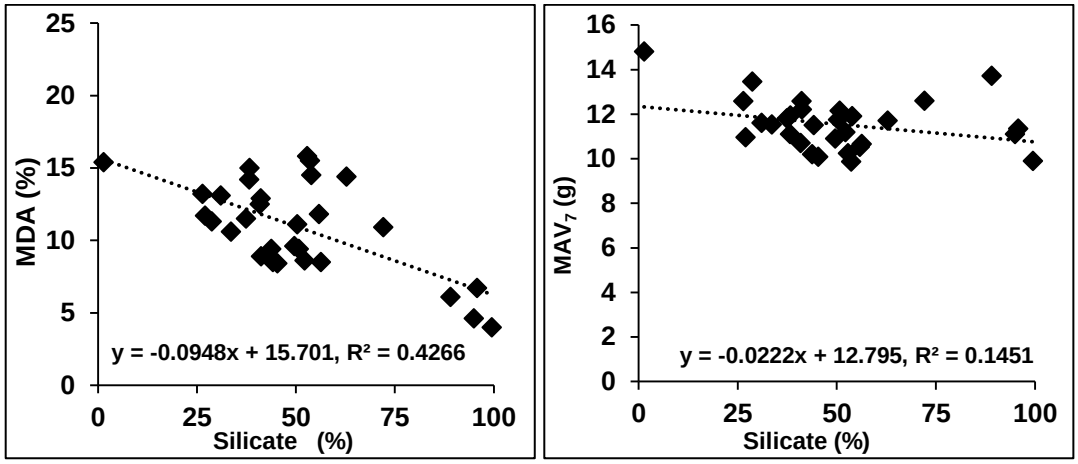


Figure 19. Relationship between MDA and Silicate Mineral content (LS-616)

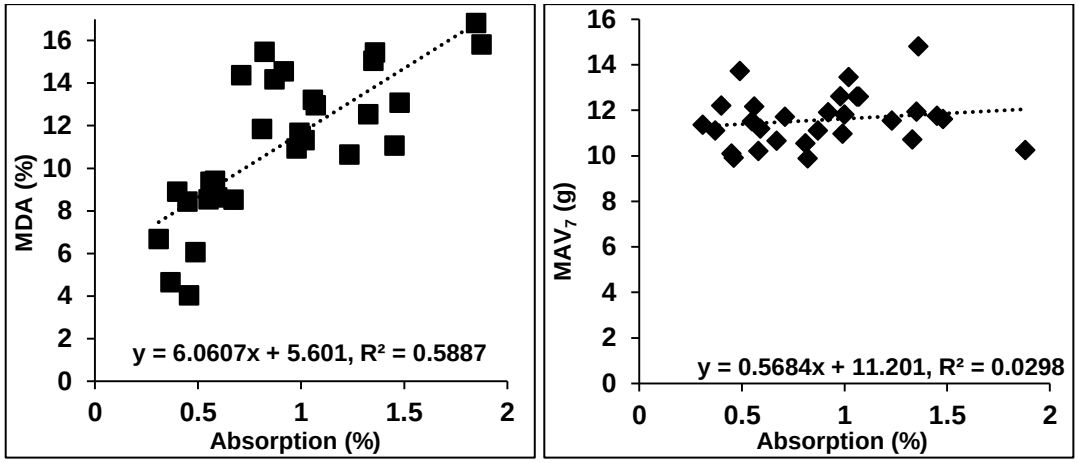


Figure 20. Relationship between Abrasion Loss and Absorption of Aggregate

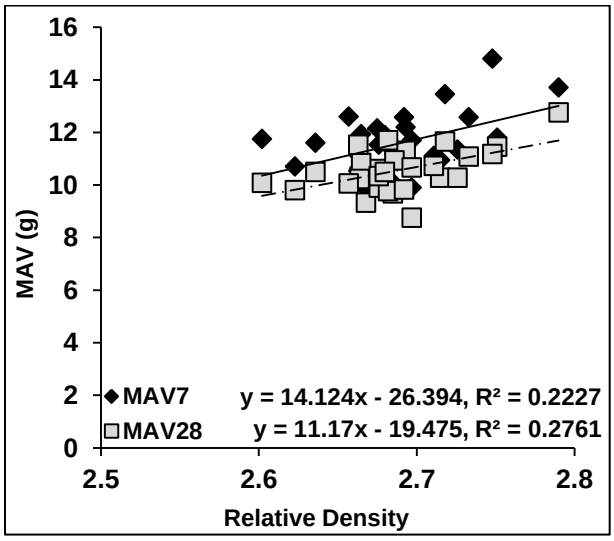


Figure 21. Relationship between MAV and Aggregate's Bulk relative density