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Evaluation of Canadian Unconfined Aggregate Freeze-Thaw Tests for Identifying Nondurable Aggregates

Santosh K. Mummaneni
Kyle A. Riding, Ph.D., P.E.
Kansas State University Transportation Center

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16 Abstract

Concrete is the most widely used material in construction. Aggregates contribute 60% to 75% of the total volume of concrete. The aggregates play a key role in concrete durability. The U.S. Midwest has many aggregates that can show distress in the field under freezing and thawing conditions. The objective of this research was to determine if the Test Method for the Resistance of Unconfined Coarse Aggregate to Freezing and Thawing, CSA A23.2-24A, could be used to differentiate good from poor performing aggregates in concrete. In this study, thirty-nine different Kansas aggregates were tested for freeze thaw resistance using a version of the CSA A23.2-24A test method modified to account for the crushed aggregate sizes used in KDOT concrete paving specifications. These results were compared to those of standard KDOT aggregate qualification tests. Twelve of these aggregates were also tested using the gradation specified in the CSA A23.2-24A standard. In addition to performing the CSA test method using a 3% sodium chloride solution, a subset of the aggregates were tested using either a 3% magnesium chloride or calcium chloride solution to determine the effects of the salt type on the aggregate performance. No correlation was found between the CSA A23.2-24A test method results and the standard KDOT aggregate qualification tests. The results also indicated that the mass loss in the CSA A23.2-24A was similar for the aggregate sizes tested. The use of $CaCl_2$ solution in the CSA A23.2-24A test resulted in lower mass loss than the use of the NaCl solution.

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Prepared by

Santosh K. Mummaneni
Kyle A. Riding, Ph.D., P.E.
Kansas State University Transportation Center

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Concrete is the most widely used material in construction. Aggregates contribute 60% to 75% of the total volume of concrete. The aggregates play a key role in concrete durability. The U.S. Midwest has many aggregates that can show distress in the field under freezing and thawing conditions. The objective of this research was to determine if the Test Method for the Resistance of Unconfined Coarse Aggregate to Freezing and Thawing, CSA A23.2-24A, could be used to differentiate well performing aggregates from poorly performing aggregates in concrete. In this study, 39 different Kansas aggregates were tested for freeze-thaw resistance using a version of the CSA A23.2-24A test method modified to account for the crushed aggregate sizes used in KDOT concrete paving specifications. These results were compared to those of standard KDOT aggregate qualification tests. Twelve of these aggregates were also tested using the gradation specified in the CSA A23.2-24A standard. In addition to performing the CSA test method using a 3% sodium chloride solution, a subset of the aggregates were tested using either a 3% magnesium chloride or calcium chloride solution to determine the effects of the salt type on the aggregate performance. No correlation was found between the CSA A23.2-24A test method results and the standard KDOT aggregate qualification tests. The results also indicated that the mass loss in the CSA A23.2-24A was similar for the aggregate sizes tested. The use of $CaCl_2$ solution in the CSA A23.2-24A test resulted in lower mass loss than the use of the NaCl solution.

Acknowledgments

The authors wish to acknowledge the financial support of the Kansas Department of Transportation (KDOT) for this research. KDOT collected the aggregates used in this project. KDOT also performed the acid insoluble tests, specific gravity, absorption, modified soundness, and concrete beam freeze-thaw tests on the aggregates. KDOT provided funds to Kansas State University (KSU) to test the aggregates collected using the CSA A23.2-24A test method, analyze the data, and write the final report. Mr. Joshua Welge was the project monitor from KDOT for the KSU project.

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Chapter 1: Introduction

1.1 Research Background

The Kansas Department of Transportation (KDOT) wants to construct durable concrete pavements with minimal maintenance needs. This goal can only be achieved by using durable aggregates that are resistant to freezing and thawing damage when used in concrete. There is a critical need for a quick and field representative test method that classifies durable aggregates from the nondurable ones. The current battery of tests used by KDOT to qualify an aggregate for use in on-grade concrete can take up to six months to complete. The Canadian freeze-thaw method CSA A23.2-24A, developed by the Ministry of Transportation Ontario (MTO) (CSA A23.2-24A 2004), was developed to quickly screen aggregates for freezing and thawing durability. The method was developed to use salt solutions instead of water to saturate the aggregates before freezing to be more representative of field conditions.

1.2 Problem Statement

Freeze-thaw deterioration of aggregates in concrete is the biggest durability problem faced by Kansas concrete pavements (Clowers 1999). The main objective of this study is to determine any correlations between the CSA A23.2-24A method and the currently used KDOT aggregate qualification methods to allow for use of the simpler and more rapid CSA test method.

1.3 Objectives and Scope of Study

The main objectives of this study were:

1. To determine the ability of the Canadian test method CSA A23.2-24A to assess the freeze-thaw resistance of unconfined coarse aggregates to freeze-thaw damage by comparison to the currently used KDOT aggregate qualification tests.
2. To determine if the use of magnesium chloride or calcium chloride salt solutions in the CSA A23.2-24A test method correlate better to the currently used KDOT aggregate qualification tests than sodium chloride salt solutions.

Chapter 2: Literature Review

2.1 Freeze-Thaw Damage Mechanism for Aggregates in Concrete

Freezing and thawing damage is one of the major causes of distress in concrete pavements. The paste portion of the concrete can be especially susceptible to freezing and thawing damage in concrete, but can be protected by the use of air-entraining admixtures (AEA) to stabilize microscopic bubbles in concrete. Concrete containing unsound coarse aggregates can deteriorate from repeated freezing and thawing cycles. There are several theories that explain frost behavior of aggregates. A theory was initially proposed, called the critical saturation theory, which stated that the freezing of water in pores will result in expansion from the phase change, stressing the pore walls and causing cracking. Collins (1944) proposed the ice lens formation theory. According to this theory, in porous materials, ice lenses are formed in a direction perpendicular to the heat flow (Smith and Williams 1990). Saturated aggregates are forced to expel water outside the particles since an increase in volume is encountered from the formation of ice. This expelled water has to move to an air void through cement paste which is a permeable medium (Van Dam et al. 2002). The pressure required for water to travel a given distance in a given time can be determined by Darcy's law as shown in Equation 2.1.

$$\boldsymbol{\Delta h = \frac{\eta}{k} * Q * \frac{l}{A}} \qquad \textbf{Equation 2.1}$$

where Δh is the pressure gradient, η is the fluid viscosity, k is the permeability, Q is the flow rate, l is the length of the flow path, and A is the flow area. If the disruptive pressures generated are greater than the tensile strength of the material, then damage occurs. This theory is only applicable to aggregates in concrete with air voids that are of the same size and equally spaced, which is not true in real concrete. This theory was later shown to have some problems as experiments have shown that the water travels towards pores between 10 μm and 10 nm in diameter (Guthrie 2002). The phenomenon of elastic accommodation can be better examined when the particle deforms elastically to accommodate an increase in volume due to pressure caused by ice formation. This parameter is a function of aggregate elastic properties and total amount of freezable water (Verbeck and Landgren 1960).

FIGURE 2.1
D-Cracks (Low Intensity) Observed Near Joint on College Avenue

Aggregates prone to freeze-thaw damage can cause D-cracking which gives a characteristic cracking pattern near the joints as shown in Figure 2-1. D-cracking is commonly observed in on-grade concrete constructed with limestone, dolomite and chert coarse aggregates, which are all sedimentary rocks (Stark 1976). Damage from D-cracking is also more predominant in the presence of deicer salts (Dubberke 1983).

2.2 Aggregate Properties Related to Freeze-Thaw Behavior

2.2.1 Porosity and Pore Size Distribution

Concrete resistance to freezing and thawing can be affected by the porosity and absorption properties of the aggregate (Mindess 2003). Freezing and thawing damage in aggregates occurs when the aggregate pores are filled with water and a freezing event occurs. During a freezing event, the water inside the pores can exert pressure on the pore walls which results in the formation of internal stresses and cracking (Hudec 1987). The aggregate pore quantity and size distribution is a major factor in the aggregate frost durability (Richardson 2009). Several studies (Hudec 1978; Kaneuji 1978; Kaneuji et al. 1980) showed that there is an interaction between pore size distribution and freeze-thaw damage. From a study done by Kaneuji it was observed that for aggregates subjected to freeze-thaw tests, aggregates with larger pore sizes indicated lower durability (Kaneuji 1978). Aggregates having large pores tend to accommodate more water into the pores (Lewis et al. 1953). This is somewhat balanced by the fact that the larger pores have a lower saturation level because they empty first during drying. The aggregate permeability also tends to be higher, which makes it easier for the water in the aggregate to escape to an entrained air void during freezing, lowering the damage level. Freeze-thaw damage is also encountered in aggregates with a large number of small pores (Hiltrop and Lemish 1960, Domaschuk and Garychuk 1988). There is a critical range of pore sizes as shown in Table 2.1, above which water frozen inside the pores can be easily expelled from the pores. (Winslow et al. 1982).

TABLE 2.1
Critical Pore Sizes Range Obtained for D-Cracking

Study	Critical Pore Size (μm)	Comments on Study
Shakoor 1982	0.01–10	Pore size was determined based on freeze-thaw results on aggregates subjected to 5% NaCl solution.
Salcedo 1984	0.045–10	Temperature and rate of temperature change was considered in determining the critical pore size for aggregates subjected to freeze-thaw.
Dubberke and Marks 1985	0.04–0.2	Critical Pore size was determined for aggregates subjected to deicer salts

For pores in the 10–0.1 μm range, the water in the pores has difficulty escaping the aggregate to reach an entrained air void before freezing damage occurs. On the contrary, very large pore sizes allow water to easily escape, reducing pressure inside pores (Richardson 2009). A study conducted to determine the relationship between pore size, durability, and insoluble residue revealed that aggregates with more than 60% of pores less than 0.1 μm were observed to be unsound (Shakoor 1982). Aggregates have been shown to exhibit lower freeze-thaw durability with large pore volumes or small pore diameters (i.e., for pore sizes larger than 6.8 μm and not smaller than 45Å) (Kaneuji 1978). The critical pore size depends on temperature change and rate of temperature change, demonstrating that freezing and thawing damage is dependent on several parameters (Salcedo 1984). Aggregates with certain types and distributions of clay and other minerals have also been shown to affect the performance of the aggregate (Hiltrop and Lemish 1960).

2.2.2 Absorption

Aggregate expansion can occur from freezing of the aggregates in saturated conditions, causing damage to the aggregate and the concrete (Powers and Willis 1949). It is believed that a majority of the expansion is from water absorption from osmotic pressures and not from ice crystal formation, since many of the aggregates also show damage in wetting and drying without freezing and thawing conditions (Hudec, 1987). Several studies have attempted to establish a correlation between the aggregate freeze-thaw durability in concrete and the aggregate absorption because the absorption is a measure of the aggregate total porosity. Some studies have shown that aggregates with low absorption values (<0.3%) have good frost resistance (Richardson 2009). A study conducted on some aggregates indicated a relationship between the absorption and durability factors (DFs). Minnesota aggregates with an absorption less than 1.5%, had DFs higher than 80, whereas the aggregates with an absorption greater than 2% had DFs less than 60 (Koubaa and Snyder 1996). Other studies have however shown that the use of absorption limits for aggregates have shown to be poor general predictors of aggregate durability for a wide range of aggregates (Kaneuji 1978).

2.2.3 Effect of Deicer Salts on Aggregate

Aggregate performance under freeze-thaw conditions may be significantly different in the presence of deicer salts. Water can be absorbed into the aggregates through osmosis. This phenomenon can be observed when deicing salts such as sodium chloride, magnesium chloride, calcium chloride are added to aggregates that are already wet. The change in chemical concentration disrupts the equilibrium for water in different size pores. In order to reestablish equilibrium, hydraulic forces develop within the pores. This phenomenon can be observed in aggregates with high clay content and fine capillary pores (Shakoor 1982, Hudec 1978). The difference in Kansas aggregate freeze-thaw behavior when exposed to different salts needs to be determined.

2.2.4 Mineralogy

Clay inclusions in aggregates and coating on aggregates have been shown to be harmful for concrete by increasing water retention and by swelling when the clay absorbs water (Buth et al. 1964; Buth et al. 1967). Some clay types, such as smectite clay, exhibit swelling, whereas other types do not and may be harmless. The methylene blue test, AASHTO TP 57 (2006), is a simple method to determine clay content contained in aggregates and was used to try to correlate clay content with aggregate freeze-thaw resistance (Yool et al. 1998). This test is based on the concept that clay materials have a large surface area and negative charge, which can be measured by an ion exchange phenomenon between the methylene blue cation and clay ions. The methylene blue test does not give much information on how damaging the clays detected will be in freeze-thaw, only an indication of the quantity of the clay. The location of clays also seems to play a role in the aggregate freeze-thaw durability. Interspersed clay in the aggregates has also been shown to be more susceptible to freezing and thawing damage than those with clays in laminations (Shakoor, 1982).

There were contradictory results obtained from various studies regarding the role of magnesium content in the aggregates. One study indicated that damage is more significant in dolomites with a calcium-magnesium ratio less than nine, although no clear connection has been made with other studies (Hiltrop and Lemish 1960).

The durability of aggregates is also considerably affected by the reactions that occur between aggregate and deicing salts under freeze-thaw conditions (Dubberke and Marks 1985). Deicer salts help the aggregates retain water for longer periods of time, keeping the aggregate pores in the concrete saturated longer which allows more water to freeze or enter the aggregate from osmotic pressure. Some aggregates have been shown to be more susceptible to salt than others.

2.3 Test Methods

The Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate ASTM C 88 (2005) was one of the first test methods developed and is still a commonly used method. It was developed to simulate ice crystallization pressures in the aggregates from sulfate crystallization during five wetting and drying cycles. However, the results obtained from the test correlate poorly with the durability of aggregates in service or in concrete beam freezing and thawing tests (Garrity and Kriege 1935). Many different aggregate freezing and thawing test methods have since been developed to better simulate freezing and thawing conditions and determine the coarse aggregate suitability for use in concrete. These test methods include:

1. NTBUILD 485 Standards
2. EN 1367-1 European Standards of Freeze-Thaw Testing
3. Icelandic standard method
4. The Washington Hydraulic Fracture Test (WHFT)
5. Modified Hydraulic fracture method
6. Iowa Pore Index test method
7. Coarse Aggregate Freeze-Thaw Test TEX-432-A
8. NDR Standard Method (Modified AASHTO T 103) Soundness of Aggregates by Freezing and Thawing
9. Test Method for unconfined coarse aggregate to Freezing & Thawing CSA A23.2-24A

2.3.1 NTBUILD 485

The NTBUILD 485 standard is performed on 4 to 63 mm diameter aggregates. In this test, aggregates of a narrow particle size range are soaked in either pure water or 1% NaCl solution at atmospheric pressure for 24 hrs. Aggregates exposed to deicer salts and regular freeze-thaw cycles are subjected to 1% NaCl salt solution. The salt solution must be maintained at least 10 mm above the aggregates throughout the soaking period. Table 2.2 shows the quantities of different aggregate sizes used in the test. Field conditions are thought to be better represented by using 1% NaCl in deionized water instead of distilled water.

TABLE 2.2
Quantities of Different Size of Aggregates in the Sample (NTBUILD 485 2004)

Aggregate Size (mm)	Mass or Volume of Aggregate Required	
	Normal Aggregate (grams)	Lightweight Aggregate, Bulk Volume (mL)
4–8	1000	500
8–16	2000	1000
16–32	4000	1500
32–63	6000	–

The aggregates are washed and dried to a constant mass in an oven at 230°F ± 9°F. After cooling, the aggregates sizes are weighed before soaking and freezing. The sample containers should be placed in the freezer so as to not touch each other, with a minimum spacing of two inches. The samples present in the cabinet are subjected to ten freezing and thawing cycles, with the temperature at the center of the cabinet used as the reference and control temperature. The aggregates are cooled from 68°F ± 5°F to 32°F ± 2°F over a period of 150 minutes ± 30 minutes. (NTBUILD 485 2004). The specimens in the cabinet are then maintained at 30.8°F to 32°F for 210 minutes ± 30 minutes and then further reduced to 0 ± 4.5°F over a 180 ± 30 minute period. This low temperature should be maintained for at least 240 minutes. After each cycle of freezing the specimens are subjected to thawing at 68°F ± 5.4°F. The maximum thawing period allowed for this test is 10 hours. Each freeze-thaw cycle takes 24 hours to complete. The percentage mass loss after the freezing and thawing cycles is calculated by Equation 2.2:

$$\mathbf{F} = \left(\frac{w_1 - w_2}{w_1}\right) * 100 \qquad \textbf{Equation 2.2}$$

where F is the percentage mass loss due to freeze-thaw, W_1 is initial dry mass of the test specimens before cycling (g), W_2 is the final dry mass of the t test specimens after cycling that is retained on the specified sieve (g), (NTBUILD 485 2004). For the NTBUILD 485 test, the average of the three specimens test specimens is used for aggregate qualification.

2.3.2 EN 1367-1 European Standards of Freeze-Thaw Testing

The EN 1367-1 test method is similar to NTBUILD 485, except that fresh water is used instead of 1% NaCl. Single-sized test aggregates are soaked initially in water at atmospheric pressure. These test aggregate samples are then subjected to 10 freeze-thaw cycles which includes cooling to 0°F under water and thawing at 68°F in a water bath (EN 1367-1 2007). After the end of freeze-thaw cycles, the specimens are washed and sieved and the residue is dried and cooled. The mass loss is calculated based on weights obtained by combining the residues from the three test specimens, with the mass of residue obtained expressed as a percentage of the mass of the combined test specimens (EN 1367-1 2007). The freeze-thaw loss (F) is calculated according to Equation 2.2.

2.3.3 Icelandic Standard Method

Icelandic pavements are subjected to around 100 freezing and thawing cycles every year. De-icing salts are commonly used in urban areas in Iceland. This method was introduced as CEN 154/TG 9 in an attempt to improve on EN 1367-1 and be more representative of actual field conditions. The aggregates in this test are subjected to ten daily cycles between 24.8°F to 39.2°F for a total of 70 cycles using a 1% salt solution. This method is, however, not commonly used worldwide because it failed to adequately mimic field conditions and the lack of test data from aggregates outside of Scandinavia (Pétursson and Schouenborg 2004).

2.3.4 Washington Hydraulic Fracture Test (WHFT)

The Washington Hydraulic Fracture Test (WHFT) method is a rapid method used to detect D-cracking aggregates. In this method, water is forced into the pores of the oven-dried aggregate particles by using a pressurized nitrogen source (Embacher 2003). The compressed air inside the aggregate pores expands and thereby expels water due to a sudden pressure release, creating internal stress. Aggregates whose pore structure is resistant to high pore pressure release are not susceptible to fractures. Freeze-thaw durability of the aggregates can be determined by observing the amount of fracturing that occurred on aggregates. This test is inexpensive and faster than most other methods. The WHFT is used on coarse aggregate particles varying from 3/4 inch to 1 1/4 inches. The container dimensions used in the test have a 10 inch diameter and are 2 inches deep. These containers can usually accommodate 5.6 to 6.6 lb. of aggregate. The aggregates are first treated with a silane solution to prevent saturation which would also reduce damage from pressurization (Embacher and Snyder 2003). The aggregates are pressurized using nitrogen at 1150 psi, which pressurizes the air in the pores (Embacher and Snyder 2003). A sudden release of the pressure creates large internal stresses in the aggregates which may result in fracturing (Embacher and Snyder 2003). This pressurization and depressurization treatment is repeated ten times. Aggregate particles are oven dried and sieved using 3/8 inch and no. 4 sieves. The aggregate mass retained over each sieve is determined. This process is repeated for the particles larger than 3/8 inch until 50 cycles have been reached. The percentage of fractured particles during each ten cycles of pressurization (Embacher and Snyder 2003) is given by Equation 2.3:

$$\boldsymbol{FP}_{\mathbf{i}} = \left(\frac{\mathbf{N_{4i}} + \mathbf{N_i} - \mathbf{N_0}}{\mathbf{N_0}}\right) * \mathbf{100} \qquad \textbf{Equation 2.3}$$

where N_{4i} = number of particles passing the 3/8 inch sieve and retained on the no. 4 sieve after i pressurization cycles, N_i is the number of particles retained on the 3/8 inch sieve, and N_0 is the number of particles initially tested. The Hydraulic Fracture Index (HFI) can be defined as the number of cycles required producing 10% fractured aggregates and is given by Equation 2.4 (Embacher and Snyder 2003):

$$\boldsymbol{HFI} = \boldsymbol{A} + \mathbf{10} * ((\mathbf{10}\text{-}\boldsymbol{FP_A})/(\boldsymbol{FP_B}\text{-}\boldsymbol{FP_A})) \qquad \textbf{Equation 2.4}$$

where A is the number of cycles just prior to achieving 10% fracturing, FP_A is the percentage of fracturing just prior to achieving 10% particle mass loss and FP_B is the percentage of fracturing just after achieving 10% particle mass loss. If 10% fracturing doesn't occur by the end of 50 pressurization cycles, then the HFI is calculated according to Equation 2.5 (Embacher and Snyder 2003):

$$\boldsymbol{HFI = 50 * (10/FP_{50})} \qquad \textbf{Equation 2.5}$$

where FP_{50} is the percent fracturing after 50 pressurization cycles.

2.3.5 Modified Hydraulic Fracture Testing Procedure

The Washington Hydraulic Fracture Test (WHFT) Method was modified to better simulate fracture from freezing and thawing. One change was to include aggregate mass retained on additional sieve sizes. The aggregate size fractions used in the modified test method are 3/4 to 1 1/2 inches, 1/2 to 3/4 inches and no. 4 to 1/2 inch. A larger chamber is used in the modified test to accommodate more aggregates with the goal of reducing variability (Embacher and Snyder 2003). The data for the modified hydraulic fracture test has to be normalized because of the different size samples used. Normalization is done by establishing a comparison between mass of particles retained on each sieve after 50 cycles to the mass of aggregate sample on each sieve at zero pressurization cycles. Replicate samples are not required with this method because of the large sample size (Embacher and Snyder 2003).

2.3.6 Iowa Pore Index Test

In the Iowa Pore Index test, 35 psi of air pressure is used to inject water into oven-dried aggregates during a period of 1 to 15 minutes. The amount of water injected into the aggregates is measured. The volume of water absorbed during the first minute is the primary load, and the volume intruded during the next 14 minutes is the secondary load. The Iowa pore index quality number is given by Equation 2.6 (Dubberke 1998):

$$\mathbf{IQ} = \left(\frac{\boldsymbol{SL}}{\mathbf{PL - 10}}\right) * \mathbf{V} * \mathbf{0.55}$$ **Equation 2.6**

where *IQ* is the Iowa Pore Index Quality number, *SL* is the secondary load, *PL* is the primary load, and *V* is the volume. This test can effectively identify aggregates with 0.04 to 0.2 micron diameter size pores and has been shown to correlate to the aggregate service records in Iowa. This test might, however, give misleading results with nonhomogeneous aggregate samples. Tests conducted using the Iowa Pore Index Test method indicate that D-cracking is generally found in aggregates which are fine grained and durable aggregates are either coarse grained or extremely fine grained (Dubberke 1998).

2.3.7 Coarse Aggregate Freeze-Thaw Test Texas DOT Designation: TEX-432-A

In the TEX 432-A method, aggregates are sieved using the weights of the individual size fractions shown in the Table 2.3 (TEX-432-A 1999).

TABLE 2.3
Weights of Individual Aggregate Size Fractions Used in the TEX-432-A Method

Size of aggregate		Weight of Individual Sizes (grams)
Passing (inches)	**Retained (inches)**	
3/4	5/8	400 ± 10
5/8	1/2	250 ± 10
1/2	3/8	200 ± 10
3/8	No. 4	100 ± 5
No. 4	No. 8	30± 5

Aggregates are initially soaked in trays for 24 hours and then subjected to two hours of freezing at 15°F. Aggregates are thawed in water at room temperature until there is no evidence of ice in the water. Fifty freezing and thawing cycles are used after which the aggregates are then dried and weighed. The percentage loss for each size fraction is calculated as shown in Equation 2.2 (TEX-423-A 1999).

2.3.8 NDR Standard Method T 103, Soundness of Aggregates by Freezing and Thawing

The Nebraska Department of Roads (NDOR) test method, T 103, aggregates are frozen at -15°F for 90 minutes and thawed for 30 minutes in a tank of 0.5% methyl alcohol at 70°F to 81°F. After sixteen cycles of freezing and thawing, the samples are oven dried at 230°F ± 9°F to constant weight. The samples are finally sieved through a no. 8 sieve and weighed. The percent passing though the no. 8 sieve is calculated as the percent loss which is an indicator of freeze-thaw durability (NDR T 103 2011).

2.3.9 CSA A23.2-24A Test Method for Unconfined Coarse Aggregate to Freezing and Thawing

The CSA A23.2-24A (2004) test method was developed by the University of Windsor in association with Ministry of Transportation Ontario. In this method, samples are sieved with the mass of each aggregate sieve size needed for the test shown in Table 2.4.

TABLE 2.4
Quantities of Different Sizes Present in the Sample (CSA A23.2-24A 2004)

Weights of Test Sample		
Passing (mm)	**Retained (mm)**	**Mass (g)**
40	28	5000
28	20	2500
20	14	1250
14	10	1000
10	5	500

Aggregates are placed in containers such that aggregates coarser than 3/4 inch are placed in two, one liter containers. The aggregates in the container are immersed in a 3% NaCl solution. The containers are sealed to prevent evaporation and are kept at room temperature for 24 ± 2 hrs. After one day of soaking, the containers are drained using a 1/5 inch mesh. The containers are sealed before freezing to prevent drying. Spacers are installed between containers to prevent contact. The baskets are then placed in a freezer at -0.4°F ± 3.6°F for 16 ± 2 hours. After removing the aggregate containers from the freezer, they are thawed for 8 ± 1 hours at room temperature. After each thawing period, all aggregate containers are turned one quarter turn before being returned to the freezer. After five cycles of freezing and thawing, the aggregates are washed with tap water five times. The water present in the container is drained, after which, the aggregates are oven dried to constant mass at 230 ± 9°F. Each aggregate is placed on the same sieve used for the sample preparation and is sieved for three minutes. The weight of aggregate retained on each sieve is recorded. The percentage of mass lost due to freeze-thaw cycles is calculated according to Equation 2.7:

$$\mathbf{F = \Sigma((M_0 – M_f) * 100 / (M_0))} \qquad \textbf{Equation 2.7}$$

where F is the total percentage loss, M_0 is the original aggregate size fraction weight before freezing, and M_f is the mass of the aggregate size fraction after the freezing and thawing cycles.

A set of control aggregates should be tested with each group of aggregate tested. Any problems with the freezing and thawing process will be apparent in the mass loss values found with the control aggregate. The Ministry of Transportation Ontario maintains a stockpile of control aggregates.

Chapter 3: Methods and Materials Used

The main objective of this project is to determine if the CSA A23.2-24A test method for the resistance of unconfined coarse aggregate to freezing and thawing can be used as a rapid and accurate method for determining the freezing and thawing durability of aggregates in concrete. This study aims to correlate the results of the CSA A23.2-24A test method to the current KDOT aggregate test methods. To accomplish this, aggregates tested by KDOT using the current KDOT aggregate qualification methods were tested using the CSA A23.2-24A method.

The current KDOT aggregate qualification tests include the following standards:

- The KTMR-21 Soundness and Modified Soundness of Aggregates by Freezing and Thawing Test Method (KTMR-21 2007) is used to test the freezing and thawing resistance of bare aggregates. Twenty-five freezing and thawing cycles are conducted on aggregates and durable aggregates are selected based on the assumption that the sum of the cumulative mass of coarse aggregates after freezing and thawing cycles must be above 85% of the initial sum of the cumulative mass of aggregates greater than the no. 8 sieve before freezing.
- The AASHTO T96 test method is used for testing the abrasion and impact resistance of coarse aggregates. In this test, sizes of coarse aggregate smaller than 1 1/2 inches are tested for resistance to degradation by impact and abrasion using the Los Angeles testing machine.
- The KTMR-28 method is used to determine the total amount of acid-insoluble residue of limestone or dolomite aggregates. In this method, the carbonate fraction of the aggregate is dissolved in hydrochloric acid, after which, the sample is filtered to collect and weigh the residue.
- The KTMR-22 test method is a modified version of the ASTM C 666 method B rapid concrete freezing and thawing test. The ASTM C 666 test is modified to include a 90 day curing period and is used as the final performance test for use of limestone aggregates in Kansas concrete pavements. The KTMR-22 test method can take up to six months to complete.

The pavement vulnerability factor (PVF) is an index of the total pore volume and siliceous material. The PVF can be calculated using Equation 3.1 (Clowers 1999):

$$\boldsymbol{PVF = \frac{100A}{A + 2.6B}} \qquad \textbf{Equation 3.1}$$

where A is the percentage by weight of acid insoluble residue, and B is the aggregate water absorption (%). Aggregates with a PVF higher than 40 were found to have poor durability (Clowers 1999). Some aggregates with a PVF less than 40 were recently found to be non-durable, causing KDOT to discontinue the use of the PVF for preliminary acceptance of aggregates pending KTMR-22 test results. However, PVF has been included in this study for comparison purposes.

A rapid test that better correlates with the results of the KTMR-22 test method would help prevent some poorly performing aggregates from being used in concrete pavements. All aggregates used in concrete pavement must be qualified by passing the KTMR-21, AASHTO T96, KTMR-25, and KTMR-22 tests. Subsequent tests on the aggregates are performed. Since the KTMR-22 can take up to six months to perform; however, any aggregates used between the last passing test and a failing test may be suspect. The CSA A23.2-24A test method for the resistance of unconfined coarse aggregate to freezing and thawing was developed as a rapid test method to screen aggregates for freeze-thaw durability. Aggregates were also tested for specific gravity and absorption using the KTMR-27 test method for comparison with KDOT results.

3.1 KTMR-27 Modified Specific Gravity and Absorption of Aggregate Test Method

Aggregates were tested for specific gravity and absorption for comparison with the KDOT values obtained. The KTMR-27 test method is similar to the AASHTO T85 procedure used to determine the specific gravity and absorption of aggregates. The main difference between these two methods is that the aggregates are soaked for 24 ± 4 hours in the KTMR-27 method, whereas the aggregates are soaked for 17 ± 1 hours before measuring the saturated surface dry (SSD) weight in the AASHTO T85 method.

The aggregates tested using the KTMR-27 method were initially sieved, washed and dried. Each sample was then recombined and weighed to give five pounds of sample passing the 3/4 inch sieve and retained on the 1/2 inch sieve and five pounds of sample passing the 1/2 inch. sieve and retained on the 3/8 inch sieve. The aggregates were soaked in water for 24±4 hrs. and then brought to a saturated surface dry (SSD) condition by drying the aggregates with a towel by hand, until the free water was removed from the aggregate surface. Aggregates were then re-immersed in a water bath as shown in Figure 3-1 at 77 ± 1.8°F and were stirred to eliminate entrapped air and weighed. The sample was then dried to a constant mass at 230 ± 9°F. The weight was recorded after the sample cooled to room temperature.

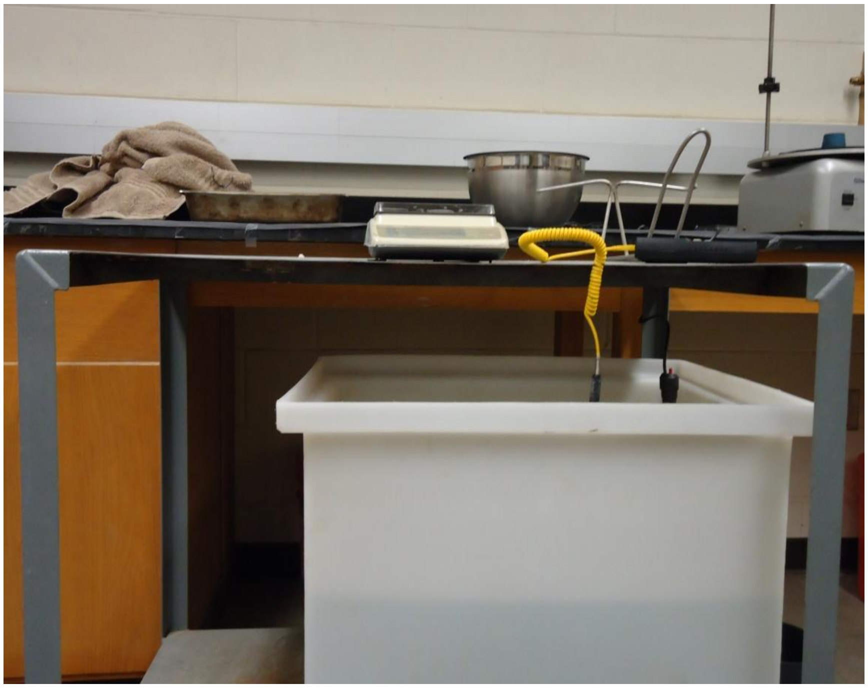

FIGURE 3.1
Apparatus for Performing the KTMR-27 Test Method

Specific Gravity and Absorption (%) were calculated using Equation 3.2 and 3.3, for different KDOT aggregates and were compared to KDOT values (ACI Educational Bulletin E1-07 2007):

$$\boldsymbol{Bulk\ Specific\ Gravity\ (BSG) = \frac{A}{B - C}}$$ **Equation 3.2**

$$\boldsymbol{Absorption}\ (\%) = \frac{(\boldsymbol{B}-\boldsymbol{A}) * \mathbf{100}}{\boldsymbol{A}} \qquad \textbf{Equation 3.3}$$

where A is the mass of oven dried Sample in air (lb.), B is the mass of saturated surface dry sample in air (lb.) and C is the mass of saturated sample in water (lb.).

3.2 Canadian Freeze-Thaw Testing CSA A23.2-24A

3.2.1 CSA A23.2-24A Test Procedure

The CSA A23.2–24A (2004) test method was developed by the University of Windsor, in association with the Ministry of Transportation Ontario (MTO). Aggregates were exposed to a salt solution and then subjected to five unconfined freezing and thawing cycles. After the freezing and thawing cycles, the aggregates were re-sieved, with the mass loss of each aggregate size determined. In the CSA A23.2-24A test method, aggregates are separated by size and each size aggregate is tested in a separate container. Aggregates retained on the 1/4 inch sieve were tested and pre-sieved using a mechanical sieve shaker.

Each aggregates size was placed in a separate plastic autoclavable container that was then filled with 3% by mass of NaCl solution for 24±2 hours at room temperature. The solution inside each container was rapidly drained by inverting the container while covered with a mesh with openings smaller than 1/5 inch for five seconds. All containers were then sealed to ensure 100% humidity and were arranged in trays with wooden spacers in between each container. This was done to ensure that no two containers touched each other. These trays were placed in a large chest freezer at -0.4°F ± 3.6°F for 16 ± 2 hours followed by thawing for 8 ± 1 hours at room temperature. All containers were turned one quarter turn between each cycle of freezing and thawing. After five cycles of freezing and thawing, the aggregates were washed with tap water five times, drained, and oven dried to a constant mass at 230°F ± 9°F. Each aggregate set was placed on the same sieve used for the sieve analysis before freezing and thawing. The percentage mass loss on each sieve due to freeze-thaw cycles was calculated using Equation 2.7.

3.2.2 Materials Tested

Twelve KDOT aggregates were tested in accordance with the CSA A23.2-24A method using the English unit equivalents of the aggregate gradations listed in Table 3.1. Kansas limestone aggregates are crushed below 3/4 inch to improve freeze-thaw durability. Thirty-nine aggregates were tested using a version of CSA A23.2-24A modified to account for the smaller aggregate sizes found in Kansas. These samples were sieved and tested according to Table 3.2. The mass loss of each individual aggregate size tested in the standard and modified CSA A23.2-24A test method were compared in order to determine if testing the Kansas limestone aggregates using the modified method instead of the original CSA A23.2-24A would cause any loss in accuracy.

TABLE 3.1
CSA A23.2-24A Required Mass of Aggregates Separated into Different Fractions

Weights of Test Sample		
Passing (mm)	**Retained (mm)**	**Mass (g)**
40	28	5000
28	20	2500
20	14	1250
14	10	1000
10	5	500

TABLE 3.2
Required Mass of Aggregates Separated into Different Fractions (for Samples Containing 1/4–3/4 Inch Aggregates)

Weights of Test Sample		
Passing (Inches)	**Retained (Inches)**	**Weight (Pounds)**
3/4	1/2	5.5
1/2	3/8	4.4
3/8	1/4	2.2

3.2.3 Locally Available Control Aggregate

CSA A23.2-24A specifies to test a control aggregate alongside the aggregates of interest during testing. This requirement was included in the specification to detect any biases or abnormality in freezing during the testing from power loss or mechanical problems that might have otherwise been undetected. The control aggregate was obtained from the Ministry of Transportation Ontario (MTO); however, only enough of the Canadian reference aggregate from Brenchin quarry no. 2 was obtained to develop a new locally available limestone control aggregate, supplied by Midwest Concrete Materials (MCM). Table 3.3 shows the material properties for the Canadian reference aggregate obtained from the MTO.

TABLE 3.3
Material Properties for Canadian Reference Aggregate (MTO Unpublished Data 2009)

Brenchin Quarry No. 2 (Canadian Reference Aggregate)		
Test	**Mean Loss (%)**	**Range (%)**
Micro Deval Abrasion	19.1	17.5–20.7
Unconfined Freeze-Thaw Test CSA (A23.2-24A)	15.6	10.2–20.9
Sulfate Soundness Test	13.2	8–18.4
Specific Gravity	2.67	2.658–2.682

The average and standard deviation of freeze-thaw mass loss for MTO aggregate and local aggregates tested by KSU are shown in Table 3.4.

TABLE 3.4
Mean and Standard Deviation of Freeze-Thaw Mass Loss for MTO Aggregate Local Aggregate

Aggregate Type	No. of Sets	Mean	Standard Deviation
MTO Reference Aggregate	6	15.51	0.584
Local Limestone Aggregate	12	15.1	2.09

The mean loss for MTO reference aggregate (15.51%) compared very favorably with the mean loss (15.6%) result by the MTO (15.6%).

Local aggregates were sieved to the same size as described in Table 3.4 and were tested alongside the KDOT aggregates**.** Three sets of the Canadian standard aggregate were run and then sieved at one-minute intervals to determine what sieve time in the KSU sieve shaker would correspond with the three minutes of sieve time used at MTO on the standard aggregate. The cumulative percent freeze-thaw loss for each fraction of local standard aggregate was compared to the average of three sets of Brenchin quarry no. 3 standard aggregates tested at the same time as shown in Figure 3.2, Figure 3.3 and Figure 3.4. Figure 3.5 shows a comparison of the combined freeze-thaw loss (%) from all three sizes versus sieving time (minutes) for the average of six Canadian aggregate sets and 12 local limestone aggregate sets. It was found that three minutes of sieving with the KSU sieving equipment for the Canadian control aggregate yielded very similar results to that obtained by the MTO.

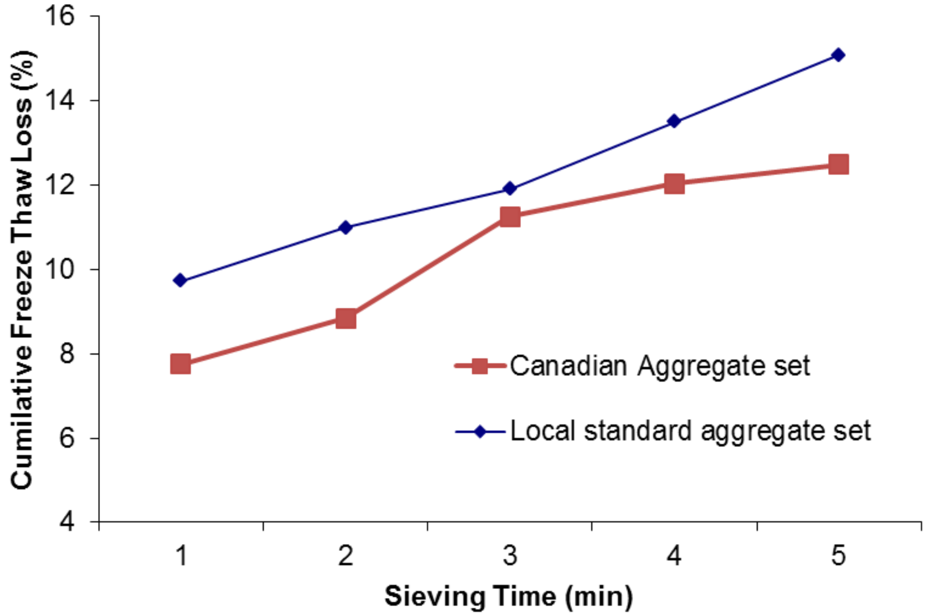

FIGURE 3.2
Cumulative Freeze-Thaw Loss versus Sieving Time for the Local Limestone Control Aggregate and the Average of Three Canadian Aggregates Sets for the 3/4–1/2 Inch Size Fraction

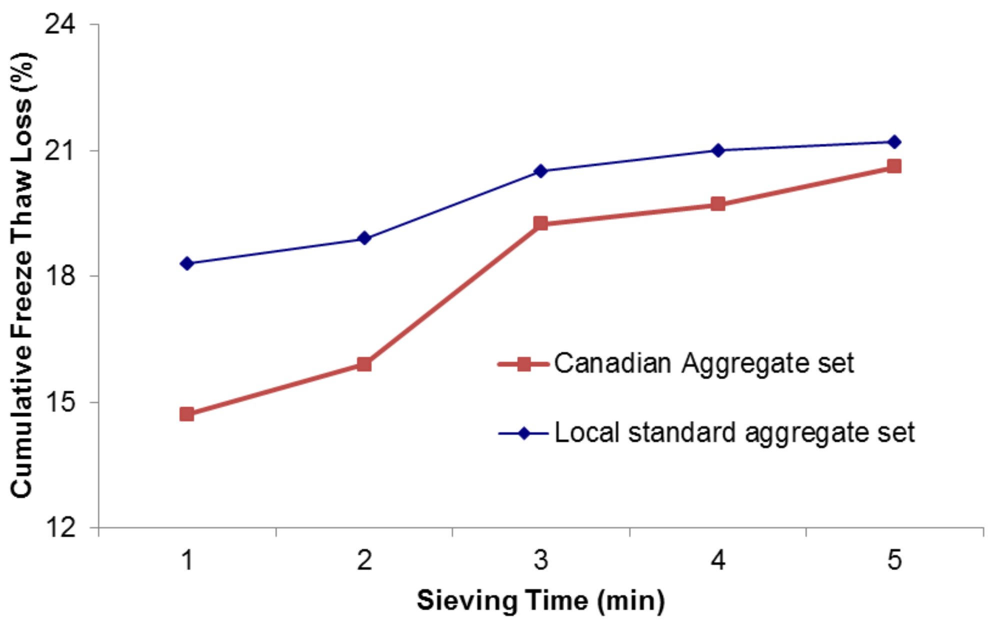

FIGURE 3.3
Cumulative Freeze-Thaw Loss versus Sieving Time for the Local Control Limestone Aggregate and the Average of Three Canadian Aggregates Sets for the 1/2–3/8 Inch Size Fraction

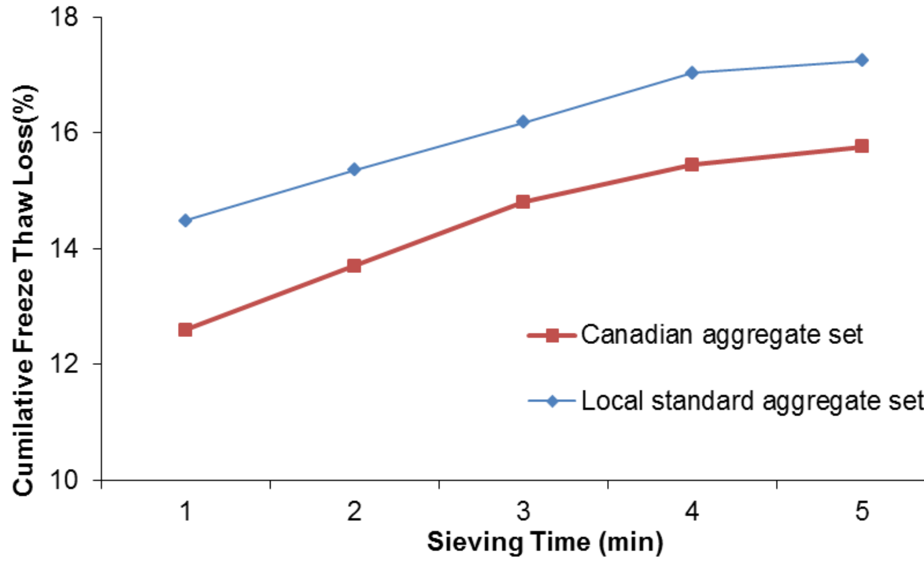

FIGURE 3.4
Cumulative Freeze-Thaw Loss versus Sieving Time for the Local Control Limestone Aggregate and the Average of Three Canadian Aggregates Sets for the 3/8–1/4 Inch Size Fraction

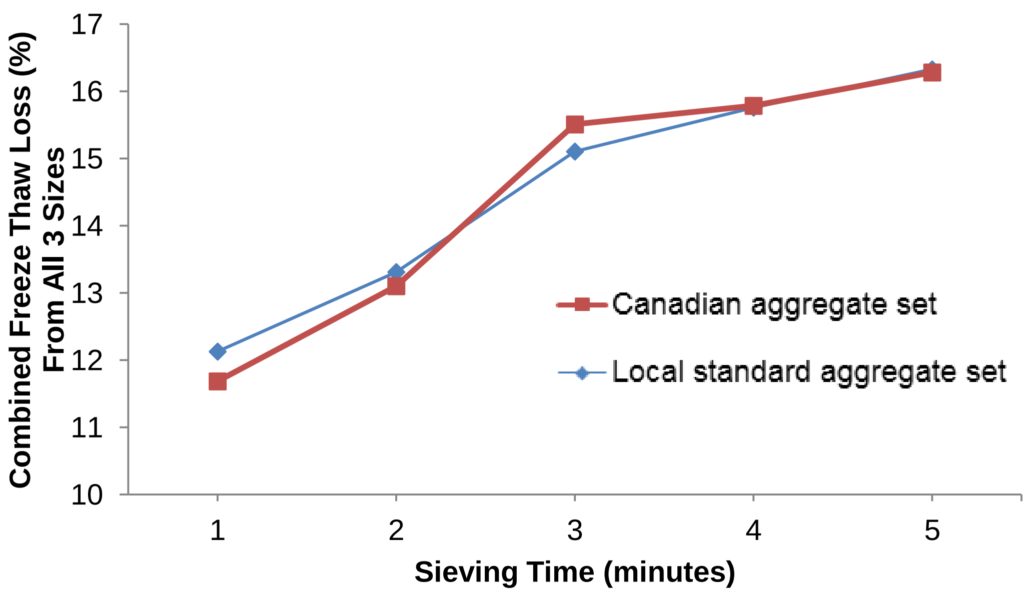

FIGURE 3.5
Comparison of Combined Freeze-Thaw Loss from All Three Sizes versus Sieving Time for the Average of Six Canadian Aggregate Sets and 12 Local Control Limestone Aggregate Sets

3.2.4 Modifications for Particle Size to Accommodate Smaller Diameter Aggregates

The CSA A23.2-24A test method requires the use of aggregates as large as 1 1/2 inches. Because KDOT specifications limit the upper size of coarse limestone aggregates for on-grade concrete to 3/4 inch, the test method was modified to use smaller aggregate sizes. Aggregates between 1/2 and 3/4 inch for the smaller diameter aggregate samples were placed in two separate one-liter autoclavable containers. The aggregates between 3/8 and 1/2 inch samples were placed in one one-liter autoclavable container, and the aggregates between 1/4 and 3/8 inch were placed in one 500 mL autoclavable bottle for testing.

3.2.5 Effects of Salt Type

The CSA A23.3-24A test method was modified to use 3% by weight $MgCl_2$ and $CaCl_2$ salt solutions. This method was used to determine if aggregate loss during freeze and thaw cycles in the presence of $MgCl_2$ or $CaCl_2$ salts would better correlate with the KTMR-22 test method. While the amount of aggregates obtained for each quarry was not sufficient to allow for testing both $MgCl_2$ and $CaCl_2$ on all aggregates, $MgCl_2$ was used on nine samples, while $CaCl_2$ was also used on seven aggregate samples to assess the effect of different salts on aggregates.

3.3 BET Nitrogen Adsorption

3.3.1 Introduction

The Brunauer Emmett Teller (BET) method was used to calculate the aggregate surface areas from measurements of physical adsorption of gas molecules (Brunauer et al. 1938). A layer of gas molecules forms on the surface of the adsorbent during the test as shown in Figure 3.6. Gas molecules adsorb onto the solid surfaces of different size pores at different pressures, which can be used in determining the specific surface area of a solid.

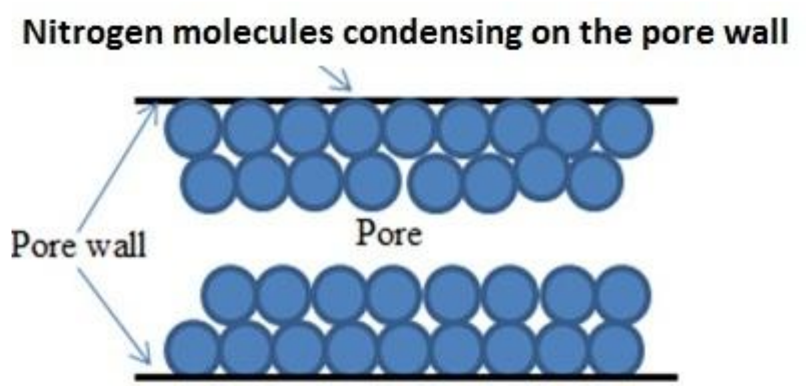

FIGURE 3.6
Gas Molecules Adsorbed on to the Surface

The BET calculations assume that the top layer atoms absorbed to the pore surface are in equilibrium with the nitrogen vapor. The BET equations are the most widely used methods for calculating the surface area of solid materials from the volume adsorbed at different vapor pressures as shown in Equation 3.4 (Brunauer et al. 1938):

$$\frac{\mathbf{1}}{\boldsymbol{W} * \left(\left(\frac{\boldsymbol{P_0}}{\boldsymbol{P}}\right) - \mathbf{1}\right)} = \left(\frac{\mathbf{1}}{\boldsymbol{W_m} * \boldsymbol{C}}\right) + \left(\frac{\boldsymbol{C} - \mathbf{1}}{\boldsymbol{W_m} * \boldsymbol{C}}\right) * \left(\frac{\boldsymbol{P}}{\boldsymbol{P_0}}\right) \qquad \textbf{Equation 3.4}$$

where W is the weight of gas adsorbed at a relative pressure, P/P_0, and W_m is the weight of adsorbate constituting a monolayer of surface coverage.

C is the BET constant, which is related to the energy of adsorption in the first adsorbed layer. The C value is an indication of the magnitude of the interactions between adsorbent and adsorbate. The C value greatly affects the adsorbate cross sectional area. Nitrogen is the most widely used gas for surface area determination due to its C value, which varies between 50 and 300 (Lowell et al. 1982). Very high C values produce significant errors in calculating cross-sectional area, making nitrogen an excellent adsorbate for cement pastes and aggregates (Lowell et al. 1982). Multi-point BET measurements were used in this study. Figure 3.7 shows the BET Autosorb 1 test apparatus used in this study.

FIGURE 3.7
BET Autosorb-1 Test Apparatus

3.3.2 Procedure

Aggregates were crushed to a diameter below 7.9 mm so that the sample would fit in the glass sample bulb as shown in Figure 3.8. The initial sample weight was obtained by subtracting the weight of the empty bulb with plug, W_1 (g), from the weight of the sample with the bulb and plug, W_2 (g).

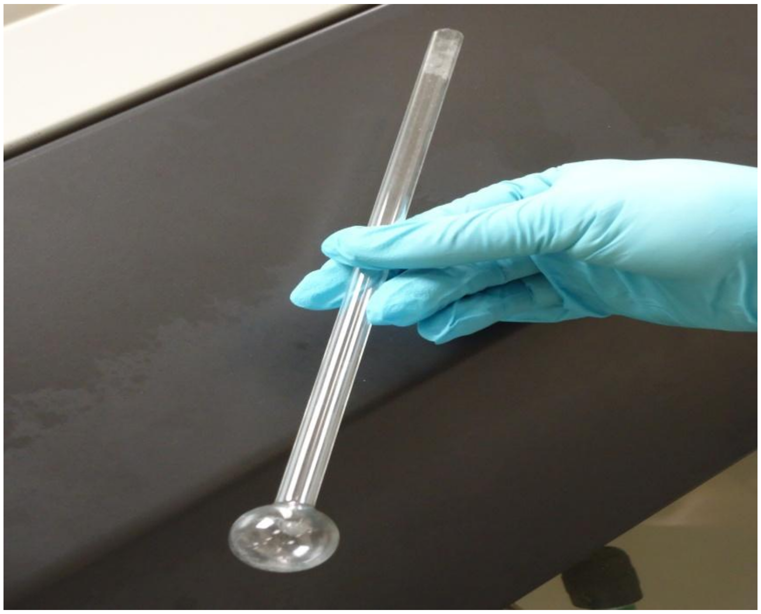

FIGURE 3.8
Bulb Used for BET Nitrogen Adsorption Testing

After the bulb was attached to the degasser using the attachments shown in Figure 3.9, the bulb is placed into the insulating bag and secured to the Autosorb 1 apparatus.

FIGURE 3.9
Final Arrangement of the Bulb

Figure 3.10 shows the arrangement of the glass bulb in the insulating heat bag. Heating was done under vacuum or continuously flowing inert gas, to ensure that all of the physically bonded impurities such as moisture were removed before testing. Figure 3.11 shows the sample in the heating bag during outgassing.

FIGURE 3.10
Bulb Placed into the Insulating Heat Bag

FIGURE 3.11
Final Arrangement of Bulb before Outgassing

An outgassing temperature of 176°F was used. After outgassing the sample for four hours. the heater in the instrument panel was turned off and the sample was allowed to cool to room temperature. The bulb was detached from the apparatus and the weight of the sample, after out gassing, was measured to make sure that there were no significant physical or chemical changes in the test samples. The true weight of the sample (original weight of sample without any existing vapors and gases adsorbed on to the surface) was calculated by subtracting the recorded weight after out gassing, W3 (g), from the initial weight W_1. After degassing, the sample was attached to the apparatus for the nitrogen to be introduced to the sample. A Dewar flask containing liquid nitrogen was placed around the sample before starting the nitrogen gas inflow, as shown in Figure 3.12.

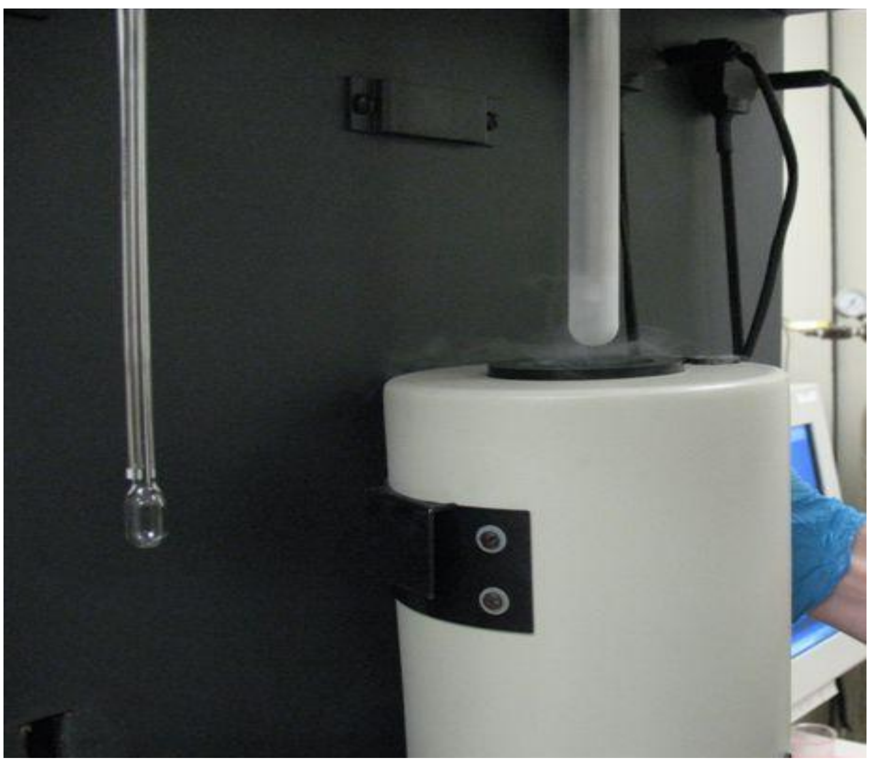

FIGURE 3.12
Dewar Being Lifted up into Its Slot after Filling Up with Nitrogen

3.3.3 Results and Calculations

The specific area can be calculated from the BET plot. An example of a sample BET plot for one aggregate sample tested is shown in Figure 3.13. The surface area of each pore A_p is calculated according to Equation 3.5:

$$\boldsymbol{A_p = 2 * \frac{V_p}{r_p}} \qquad \textbf{Equation 3.5}$$

where v_p is the volume of the pore, and r_p is the radius of the pore. The cumulative surface area was obtained by summing the A_p values.

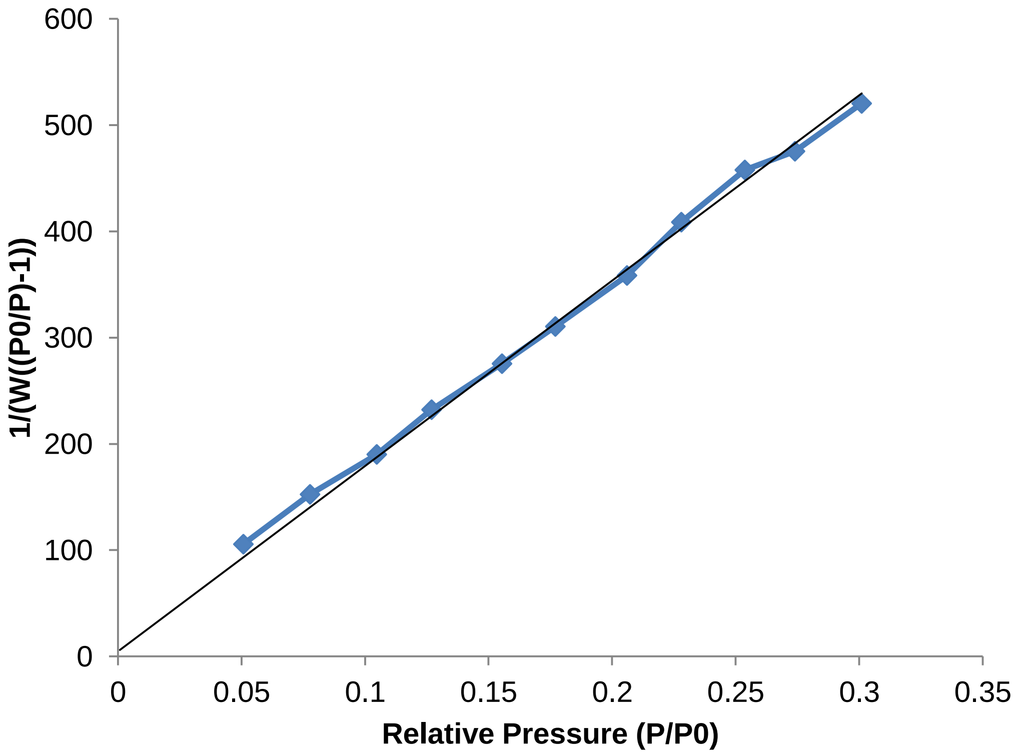

FIGURE 3.13
Typical BET Plot for KDOT Limestone Aggregate

Chapter 4: Results and Discussion

The results of the CSA A23.2-24A test method and BET nitrogen surface area experiments were compared to the standard aggregate tests run by KDOT to determine if the CSA A23.2-24A test method could be used as a more rapid substitute for the currently run tests. For the CSA A23.2-24A experiments, a modified version of the CSA A23.2-24A test method was used to allow for the testing of the smaller size aggregates. The CSA A23.2-24A method was also modified by using $CaCl_2$ or $MgCl_2$ solutions to investigate the impact of the salt solution on the aggregate durability. Tables showing the percent mass loss for the aggregates tested using aggregates sizes up to 1 1/2 inches using CSA A23.2-24A, percent mass loss for the aggregates up to 3/4 inch tested using a modified CSA A23.2-24A test method, the percent mass loss for the aggregates tested with $CaCl_2$ or $MgCl_2$, and the tests performed by KDOT are shown in Appendices A through D, respectively.

4.1 Specific Gravity and Absorption

Specific gravity and absorption were determined using the KTMR-27 procedure. Each coarse aggregate composite sample was tested for specific gravity and absorption for quality control purposes. Table 4.1 shows specific gravity and absorption values for samples with sizes between 1/4 and 1 1/2 inches. Table 4.2 shows specific gravity and absorption values for aggregate that were sampled with size fractions between 1/4 and 3/4 inches. The measured absorption and specific gravity results compared well to the values measured by KDOT, with a 0.035 average absolute difference between the KSU and KDOT results for the bulk specific gravity, and 0.55% for the absorption.

TABLE 4.1
Specific Gravity and Absorption Values for Samples Containing 1/4–1 1/2 Inch Aggregates

KDOT Lab ID	BED	Bulk Specific Gravity	Bulk Specific Gravity (SSD)	Apparent Specific Gravity	Absorption (%)	KDOT Test Results	
						BSG	Absorption
09-1468	8	2.59	2.63	2.7	1.53	2.63	3.00
09-1468	9	2.44	2.51	2.62	2.81	2.52	2.80
09-1469	1	2.52	2.6	2.75	3.36	2.6	1.40
09-1469	2	2.48	2.55	2.67	2.87	2.48	2.80
09-1884	1	2.42	2.54	2.75	4.88	2.56	1.89
09-1884	3	2.43	2.55	2.78	5.07	2.51	2.84
09-1885	1	2.55	2.59	2.68	1.96	2.58	1.80
09-1939	–	2.6	2.62	2.65	0.62	–	–
09-1940	–	2.61	2.64	2.66	0.56	–	–
09-1474	1	2.57	2.62	2.65	1.90	2.57	1.95
09-3051	2	2.47	2.55	2.59	3.10	2.47	3.00
09-3051	3	2.5	2.57	2.61	3.00	2.50	3.10

TABLE 4.2
Specific Gravity and Absorption Values for Samples Containing 1/4–3/4 Inch Aggregates

KDOT Lab I	Bed	Bulk Specific Gravity	Bulk Specific Gravity (in SSD)	Apparent Specific Gravity	Absorption (%)	KDOT test results	
						BSG	Absorption (%)
09-1008	1	2.45	2.52	2.65	3.21	2.44	3.60
09-1010	1	2.50	2.55	2.64	2.17	2.50	2.60
09-1227	1	2.54	2.60	2.71	2.50	2.57	2.00
09-1228	1	2.58	2.62	2.68	1.45	2.58	1.80
09-1231	1	2.47	2.55	2.68	3.14	2.51	2.76
09-1248	4	2.48	2.57	2.72	3.60	2.48	3.60
09-1257	1	2.59	2.63	2.69	1.50	2.59	1.50
09-1430	1	2.54	2.58	2.64	1.52	2.55	1.80
09-1454	1	2.57	2.63	2.72	2.10	2.6	1.60
09-1706	2	2.48	2.55	2.66	2.73	2.48	3.20
09-1917	5	2.53	2.58	2.66	1.92	2.52	2.60
09-1918	4	2.48	2.56	2.68	2.98	2.5	2.50
09-2257	1	2.58	2.63	2.72	2.06	2.59	1.60
09-2102	4	2.50	2.77	2.69	2.90	2.5	2.90
09-2943	5	2.52	2.58	2.68	2.40	2.52	2.94
09-2788	4	2.49	2.57	2.7	3.00	2.5	3.00
09-3497		2.45	2.52	2.58	2.50	2.53	2.2
09-3645		2.58	2.62	2.67	3.20	–	–
09-3453	3	2.62	2.63	2.68	1.20	2.54	2.30
10-0354	C	2.49	2.58	2.63	4.00	2.6	2.60
08-2058	1	2.55	2.60	2.64	1.80	2.57	3.10
09-2642	2	2.68	2.72	2.78	3.40	2.61	1.50
09-3453	4	2.54	2.59	2.65	2.70	2.55	2.60
08-355		2.65	2.71	2.74	1.80	2.57	2.20
08-2323		2.58	2.63	2.66	4.20	2.51	3.60
09-2642	1	2.50	2.61	2.67	2.80	2.46	3.0
10-0211	2	2.55	2.58	2.63	2.71	2.63	1.60
10-0424	1	2.63	2.67	2.685	2.00	2.49	2.80

The KTMR-27 test method was also used to test specific gravity and absorption values for the Canadian standard aggregate and the local control aggregate used in the project. Table 4.3 shows the specific gravity and absorption values for the Brenchin quarry no. 3 aggregates along with the local control aggregate.

TABLE 4.3
Specific Gravity and Absorption Values for Canadian Brenchin Quarry No. 4 Aggregates along with One Set of Local Control Aggregates

Specific Gravity and Absorption Values for Canadian Reference Aggregates				
Aggregate Type	**Bulk Specific Gravity**	**Bulk Specific Gravity (SSD)**	**Apparent Specific Gravity**	**Absorption (%)**
Brenchin Quarry No. 3 Aggregates	2.53	2.58	2.67	2.17
Local Control Aggregates	2.54	2.59	2.67	1.97

4.2 Effect of Particle Size on Freeze-Thaw Durability

A modified version of the CSA A23.2-24A test method was used on 39 samples supplied by KDOT containing aggregates between 1/4 and 3/4 inch. The freeze-thaw testing showed that the aggregates tested using the size fractions between 1/4 and 3/4 inch performed similar to the aggregates between 1/4 and 1 1/2 inches in the testing. Figure 4.1 shows a comparison of the 3/4 to 1/2 inch and 3/8 to 1/4 inch aggregate weight loss for all aggregates sets tested after three minutes of sieving, while Figure 4.2 shows a comparison of the 1 1/2 to 1 inches and 3/8 to 1/4 inch aggregate weight loss. Figure 4.3 shows a comparison of the 1 to 3/4 inches and the 3/8 to 1/4 inch aggregate size fraction weight loss for all aggregate sets tested after three minutes of sieving, Figure 4.4 shows a comparison of the 3/4 to 1/2 inch and 3/8 to 1/4 inch aggregate weight loss for all aggregates sets tested after three minutes of sieving.

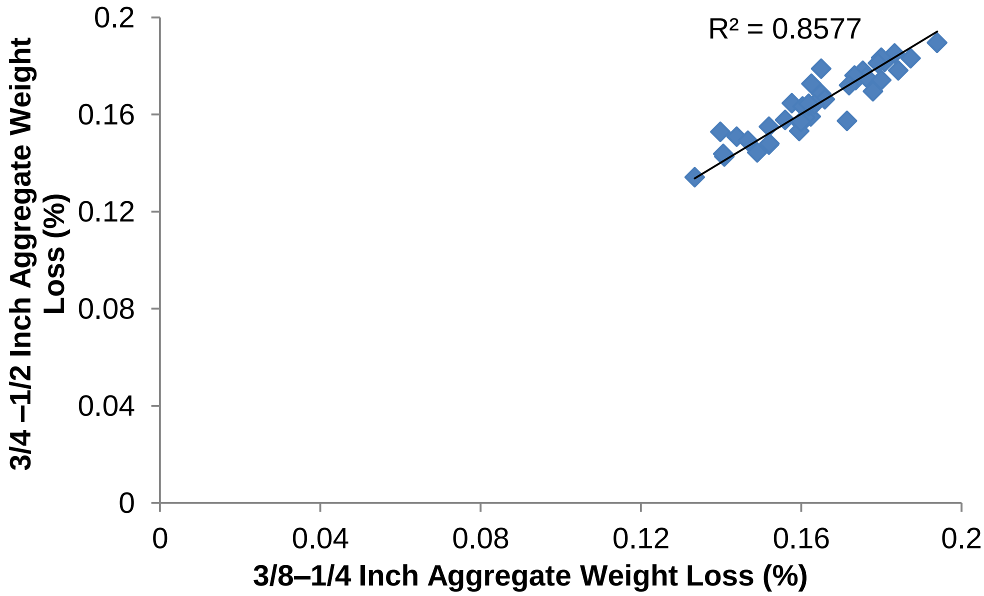

FIGURE 4.1
Comparison of Aggregate Weight Loss for the 3/4–1/2 Inch Aggregates and the 3/8–1/4 Inch Aggregates Tested

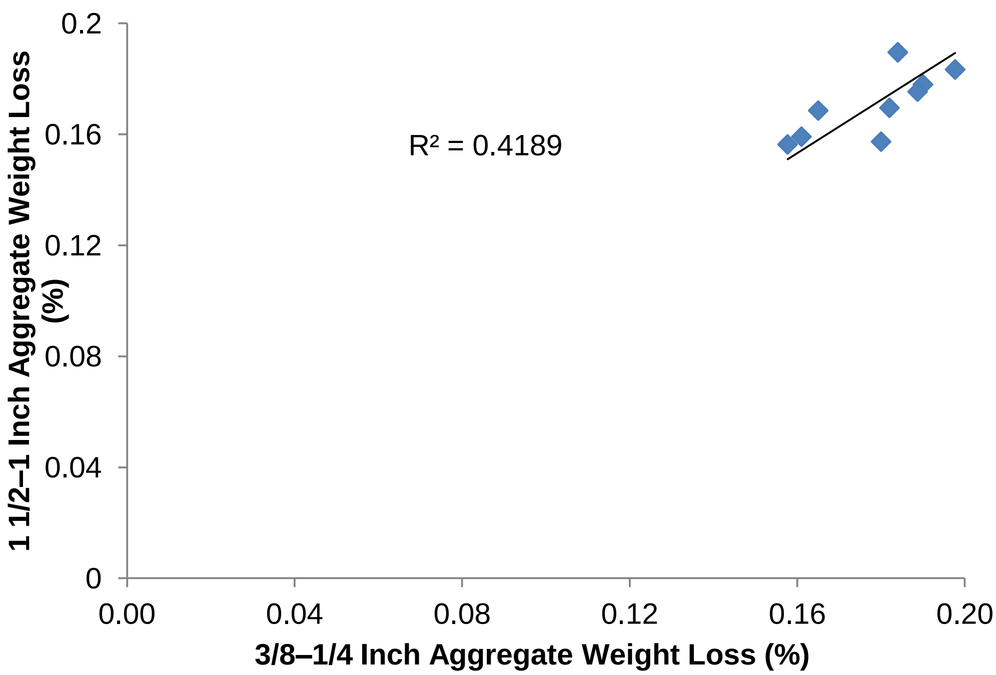

FIGURE 4.2
Comparison of Aggregate Weight Loss for the 1 1/2–1 Inch Aggregates and the 3/8–1/4 Inch Aggregates Tested

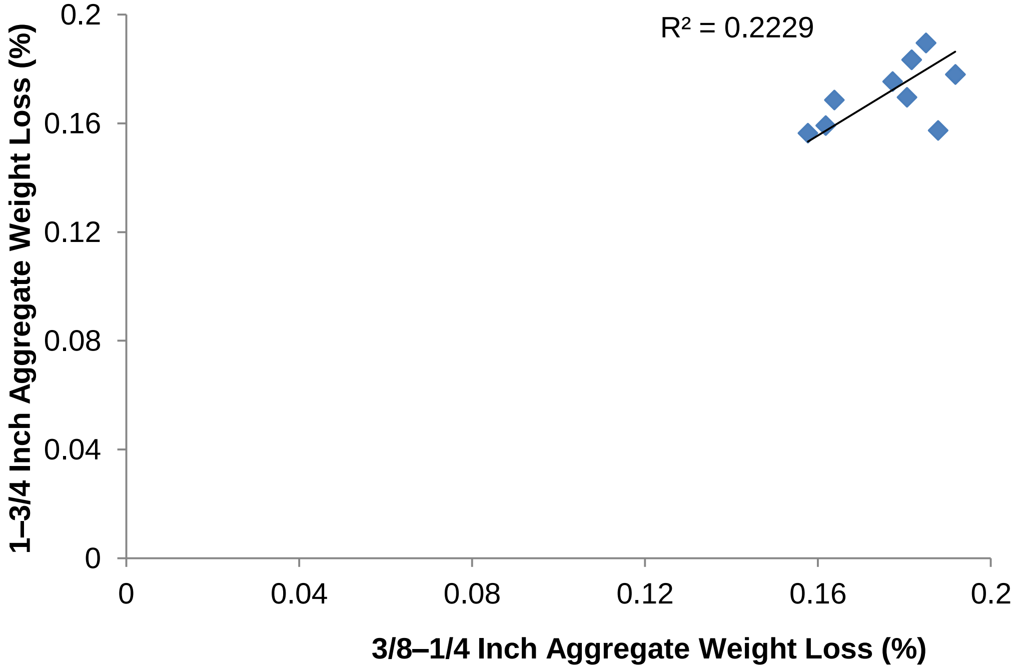

FIGURE 4.3
Comparison of Aggregate Weight Loss for the 1–3/4 Inch Aggregates and the 3/8–1/4 Inch Aggregates Tested

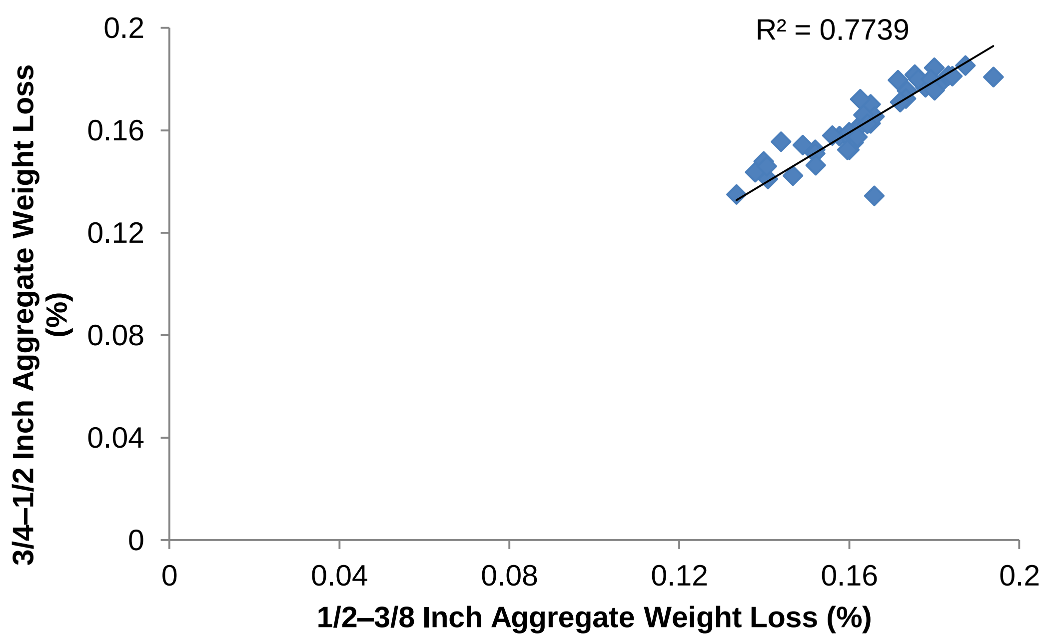

FIGURE 4.4
Comparison of Aggregate Weight Loss for the 3/4–1/2 Inch Aggregates and the 1/2–3/8 Inch Aggregates Tested

4.3 Comparison of Average Freeze-Thaw Loss of NaCl Solution with $MgCl_2$ and $CaCl_2$ Salt Solutions

The CSA A23.2-24A test method was modified to determine if the limestone aggregates in Kansas was more sensitive to some salts. The $MgCl_2$ and $CaCl_2$ salts were used instead of NaCl in the CSA A23.2-24A test method on the local control aggregate. $MgCl_2$ salt solution was used on nine of the samples that contained the larger 3/4 to 1 1/2 inch aggregates, while $CaCl_2$ salt solution was also used on seven samples containing aggregates between 1/4 and 3/4 inch. The $MgCl_2$ behaved similarly to the NaCl solution. The $CaCl_2$ solution however showed consistently lower weight loss. Figure 4.5 shows a comparison of the weight loss with the NaCl solution versus the $MgCl_2$ and $CaCl_2$ salt solution, Figure 4.6 and Figure 4.7 shows comparisons of the weight loss with sieving time for the NaCl and $CaCl_2$ solutions for KDOT aggregate 09-1008 and 09-1918. Figure 4.8 shows the effects of NaCl, $CaCl_2$ and $MgCl_2$ salts on local aggregates.

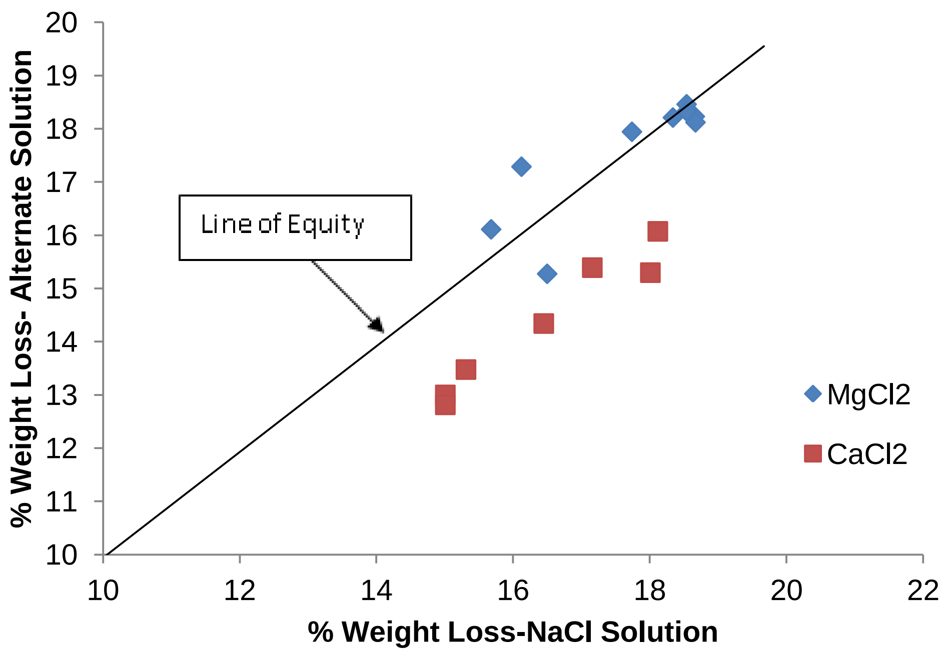

FIGURE4.5
Comparison of Aggregate Freeze-Thaw Weight Loss for NaCl versus the $MgCl_2$ and $CaCl_2$ Salt Solutions

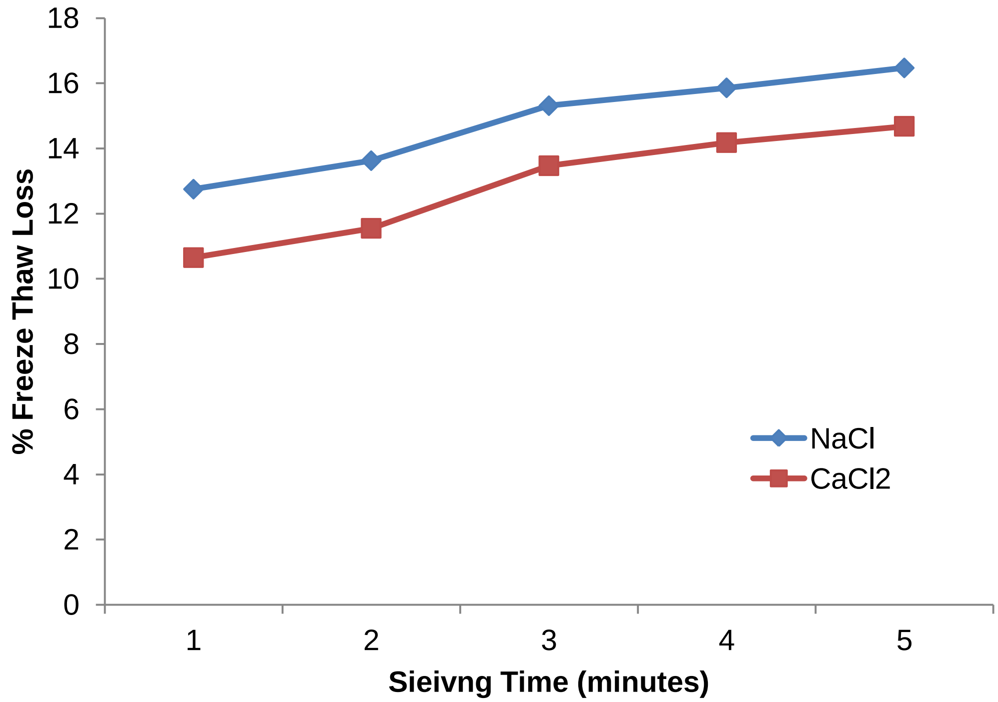

FIGURE 4.6
Comparison of NaCl and $CaCl_2$ Salt Solutions Tested Using CSA A23.3-24A. Sample 1008 with DF=99

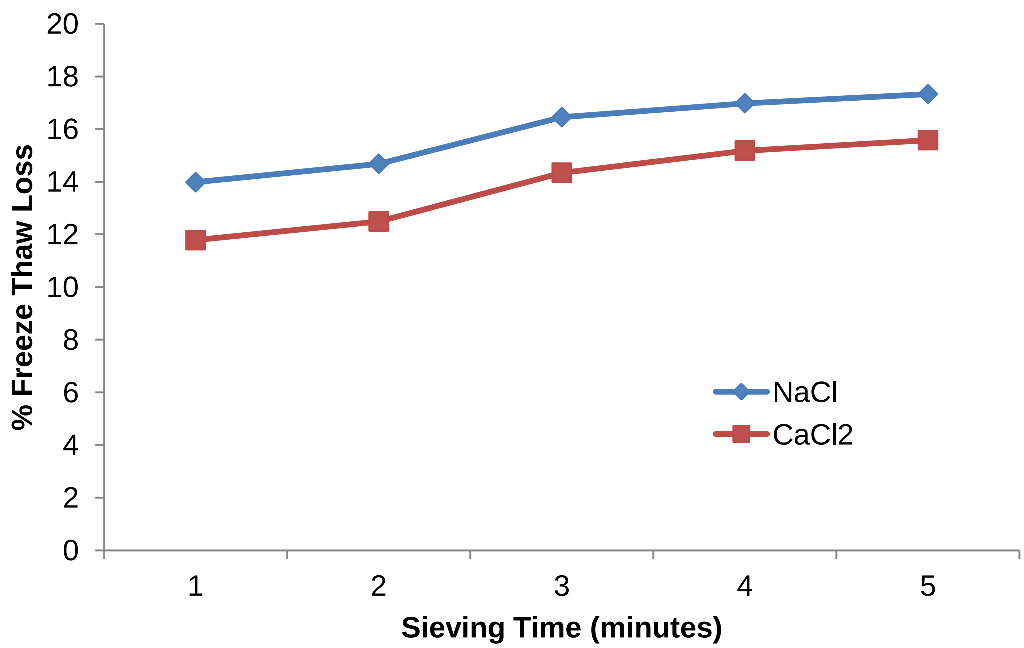

FIGURE 4.7
Comparison of NaCl and $CaCl_2$ Effects on the Freeze-Thaw Weight Loss Using CSA A23.3-24A Sample 1918 with DF=98

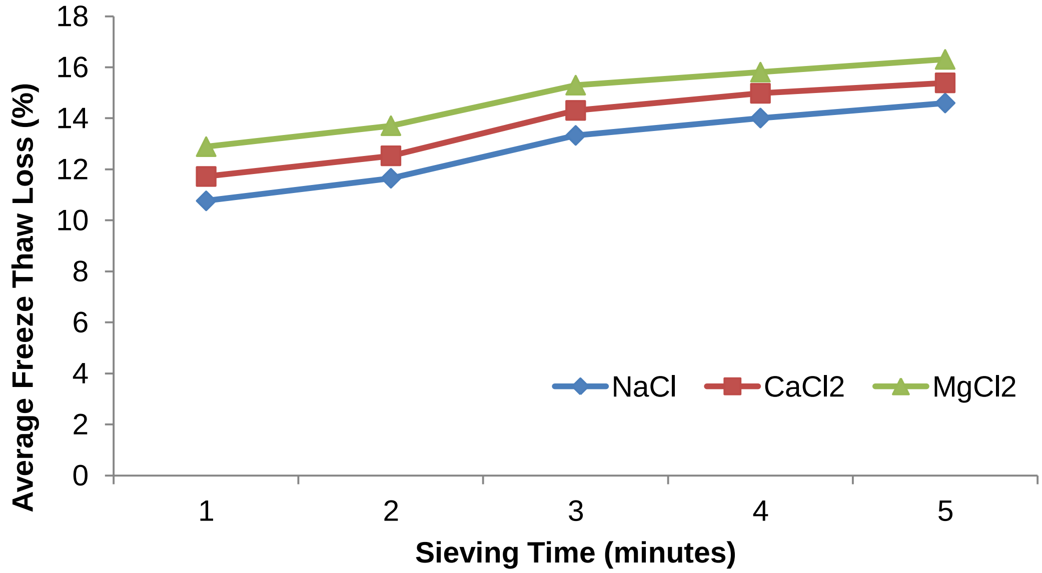

FIGURE 4.8
Comparison of Local Aggregate Freeze-Thaw Weight Loss for NaCl, $MgCl_2$ and $CaCl_2$ Salt Solutions Using CSA A23.2-24A Test Method

The same trend of mass loss with sieving time for the different salts used, with the values for each simply shifted up or down from that of the NaCl. This shows that the increase in sieving time affects the fractures developed by the different salts equally. The increased damage seen by the NaCl could be because of the higher number of ions in solution per gram of NaCl than $CaCl_2$.

4.4 Nitrogen Adsorption Experiments

BET nitrogen testing was performed on a subset of the aggregates used in this study to determine if any correlation between the aggregate surface area and freezing and thawing performance existed. BET plots were used to check for variations in volume–pressure isotherms. Figure 4.9 shows volume-relative pressure plot for Sample 09-1468 B9 which has a DF of 37, Figure 4.10 shows the BET plot for sample 09-1248 with DF of 99. Although the absolute volume of nitrogen measured in the two samples is different, no significant abnormalities are seen in the aggregate with a low DF. Figure 4.11 shows the surface area of pores of aggregates with different DFs. No correlation was seen between the KTMR-22 DF and the aggregates surface area as measured in BET nitrogen adsorption. This may be because two aggregates with similar surface areas could have very different pore volumes and size ranges.

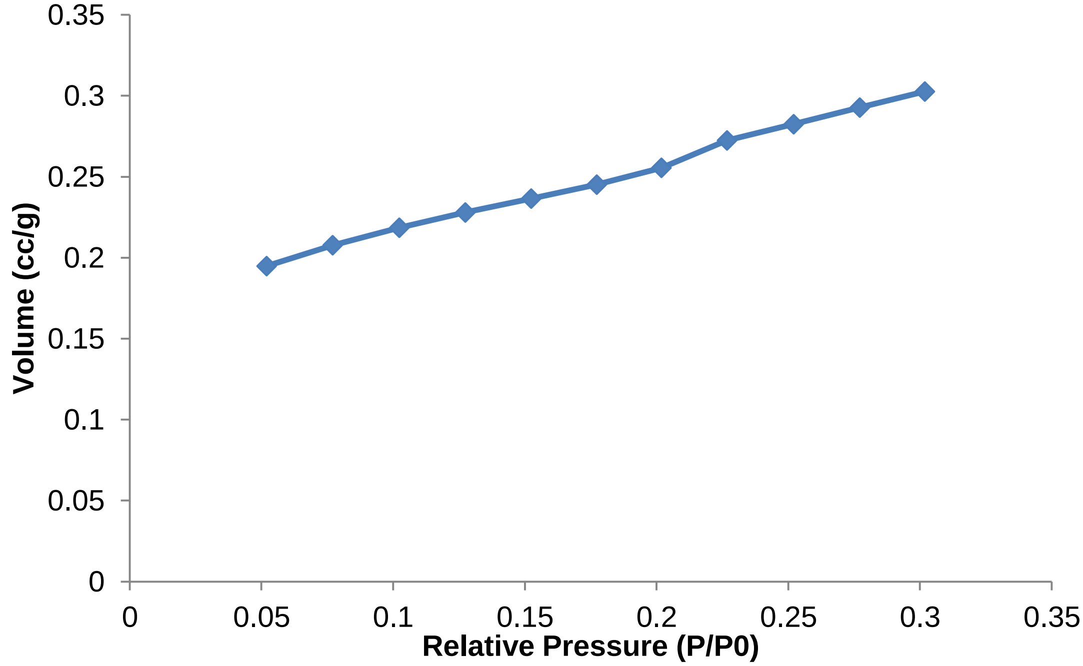

FIGURE 4.9
Linear Variation Observed in the BET Plot for Sample 09-1468 B9 with DF=37

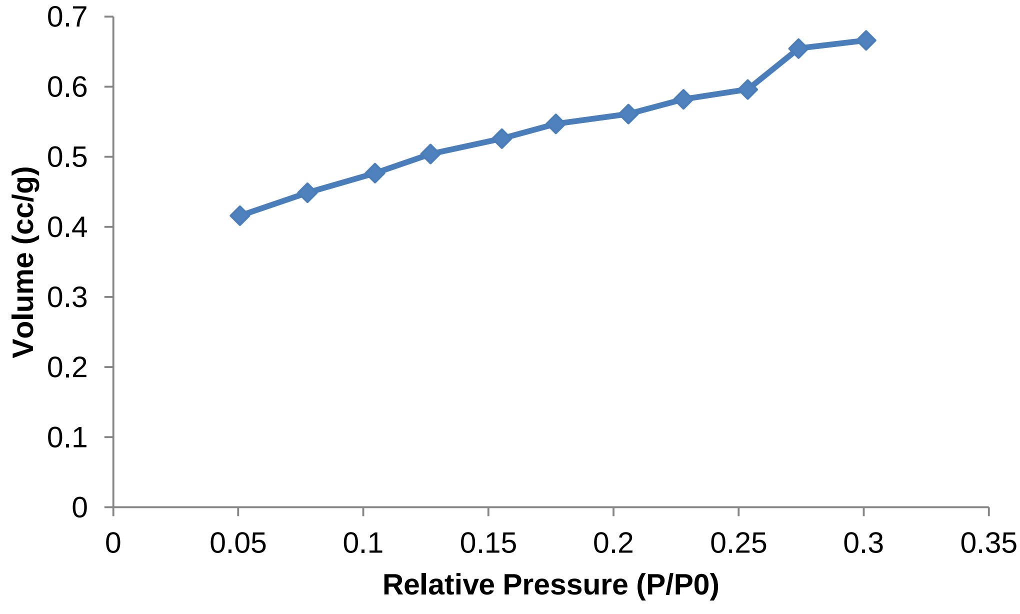

FIGURE 4.10
Volume-Relative Pressure Plot for Sample 09-1248 B9 with DF=99

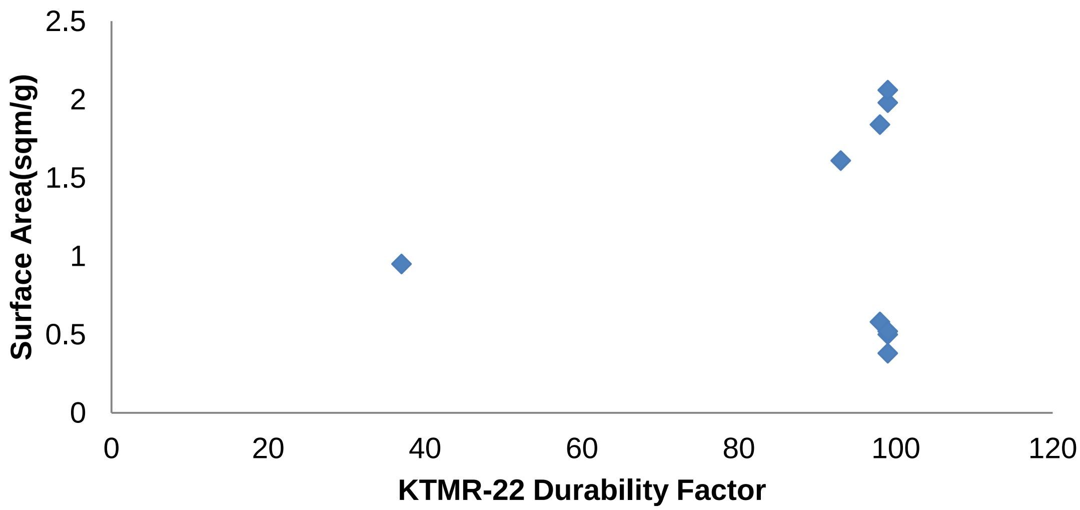

FIGURE 4.11
Comparison of KTMR-22 DFs and Aggregate Surface Area

4.5 Comparison of Average Freeze-Thaw Loss with Different Aggregate Performance Measures Done by KDOT

Comparisons were made between the 1/4 to 3/4 inch sample composite weight loss for all of the aggregate sieve fractions after sieving for three minutes and the aggregate performance measures used in this study to determine if a correlation between the test methods existed. Figure 4.12 shows the CSA A23.2-24A aggregate weight loss versus the PVF. Figure 4.13 shows the CSA A23.2-24A aggregate weight loss versus the KTMR-22 DF. Figure 4-14 shows the CSA A23.2-24A aggregate weight loss versus the aggregate modified soundness test. Figure 4.15 shows the CSA A23.2-24A aggregate weight loss (%) versus absorption values. Figure 4-16 shows CSA A23.2-24A aggregate weight loss (%) versus wear (%). The results show no correlation between the three minute weight loss (%) of the aggregates tested and currently used KDOT test methods. The results suggest that the CSA A23.2-24A test method does not clearly differentiate well and poorly performing aggregate in concrete under freezing and thawing conditions.

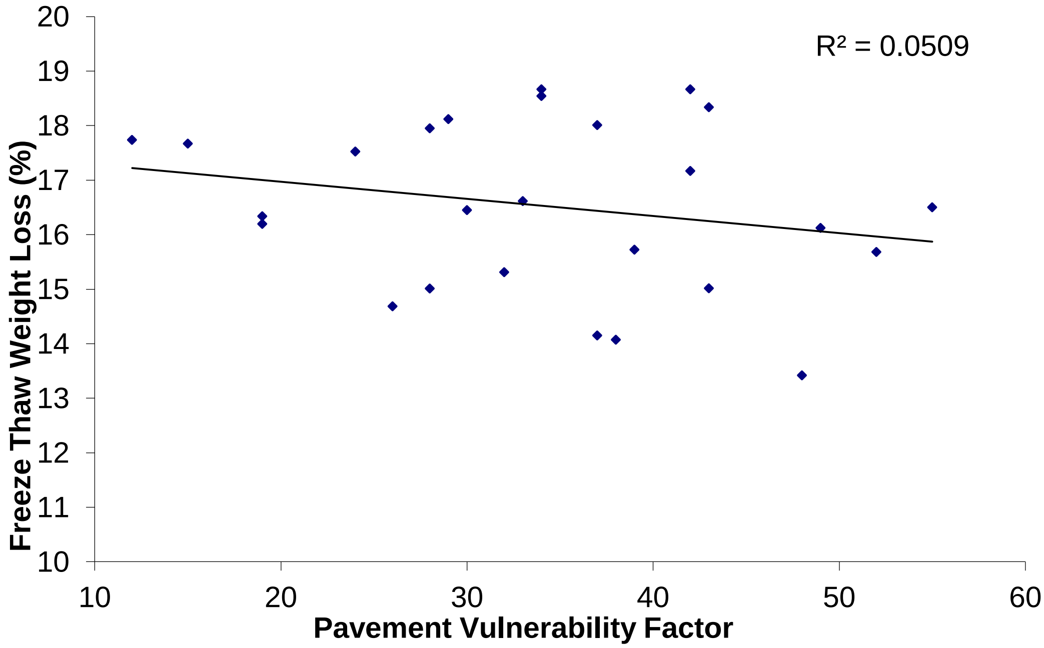

FIGURE 4.12
Aggregate Weight Loss versus PVF for KDOT Aggregates

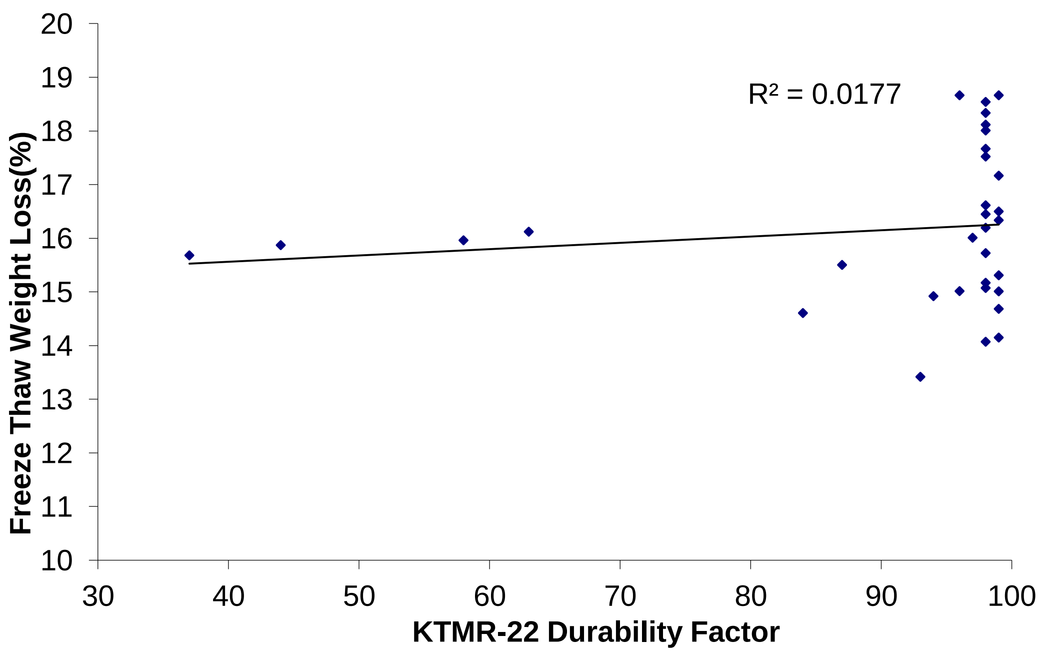

FIGURE 4.13
Aggregate Weight Loss versus KTMR-22 DF for KDOT Aggregates

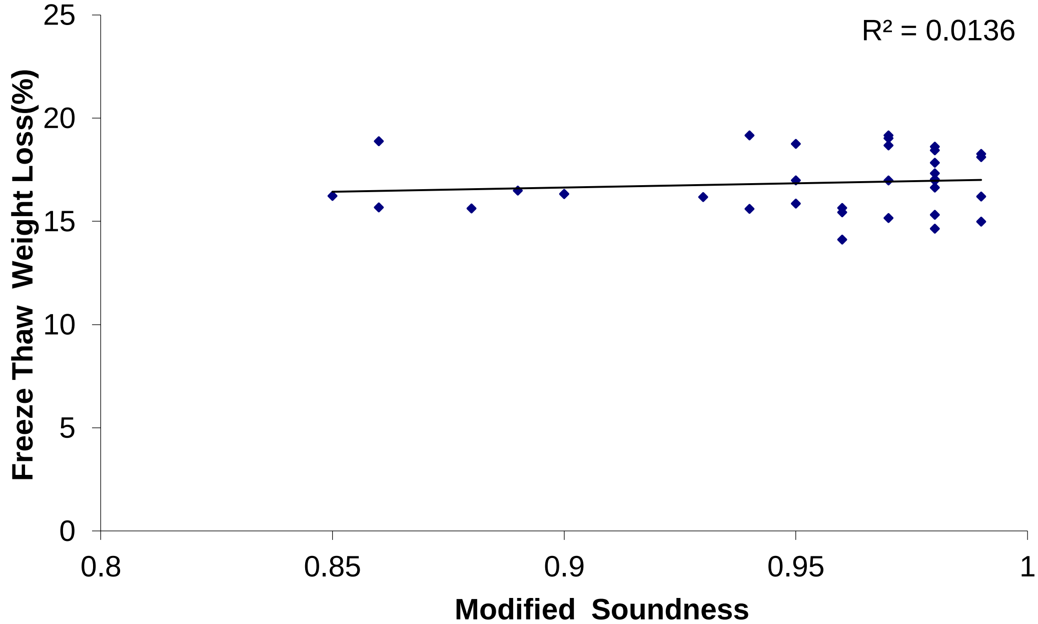

FIGURE 4.14
Aggregate Weight Loss versus Aggregate Modified Soundness Test for KDOT Aggregates

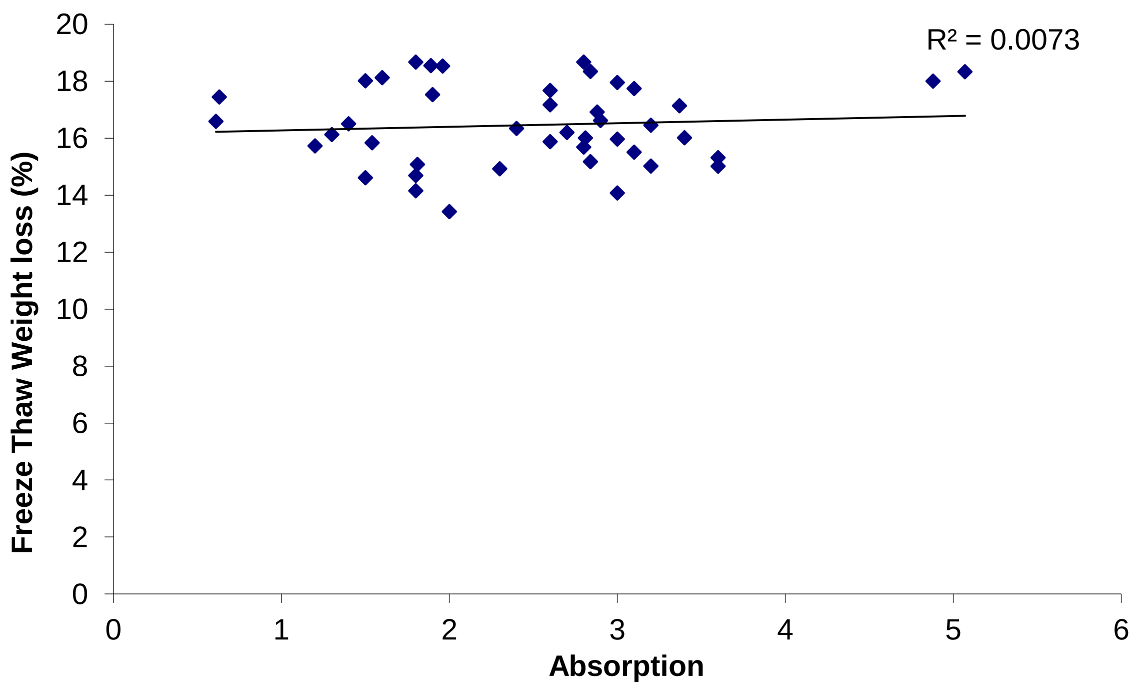

FIGURE 4.15
Aggregate Weight Loss versus Absorption Values for KDOT Aggregates

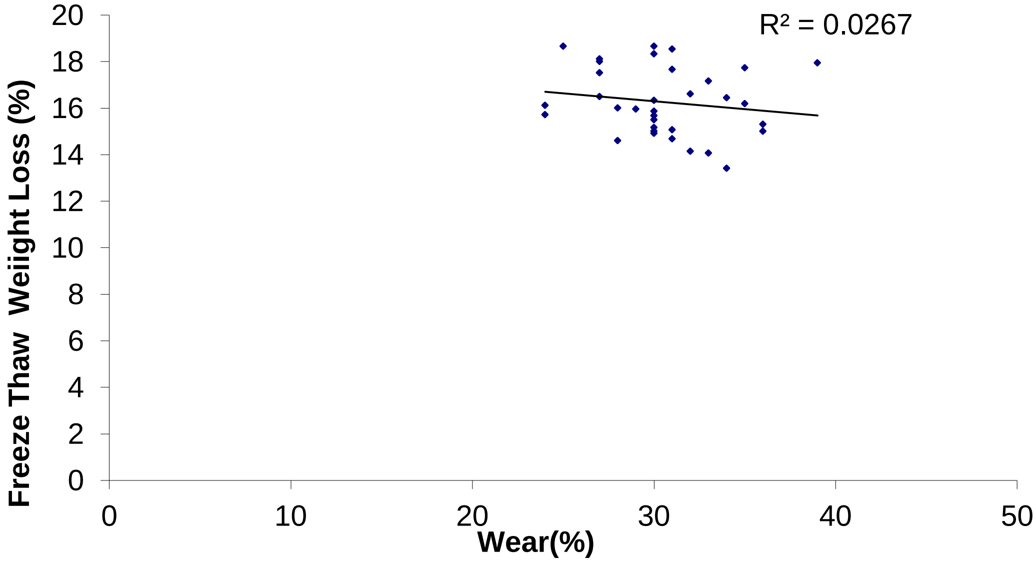

FIGURE 4.16
Aggregate Weight Loss versus Wear for KDOT Aggregates

KDOT aggregate performance measures were compared to each other to check for any possible trend. Figure 4.17 shows results from aggregate modified soundness test versus KTMR-22 DF. Figure 4.18 shows wear (%) versus KTMR-22 DF. Figure 4.19 shows the PVF versus KTMR-22 DF. The figures show no significant correlation between the aggregate performance measures, except that all of the aggregates with poor durability had PVF higher than 40.

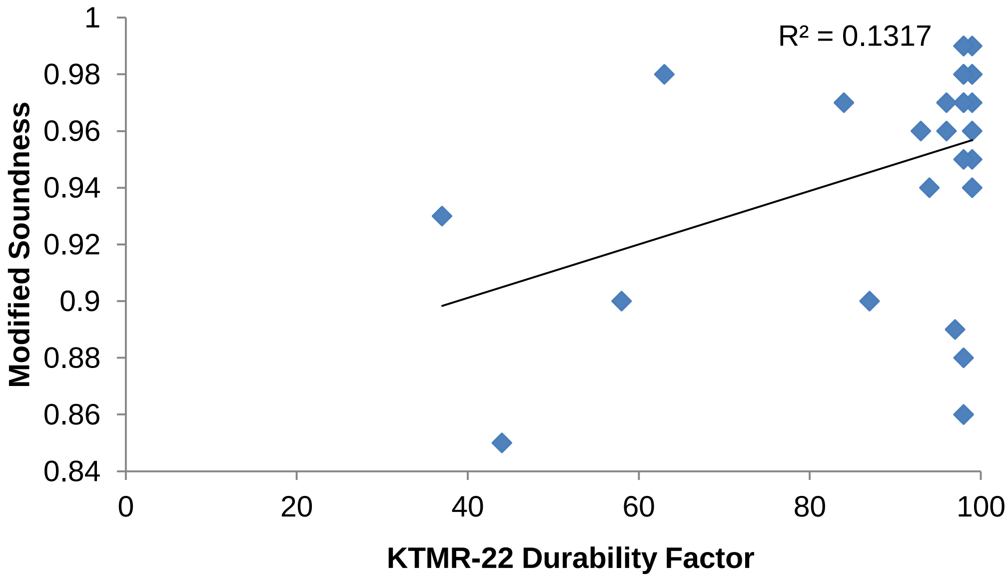

FIGURE 4.17
Aggregate Modified Soundness Test versus KTMR-22 DF for KDOT Aggregates

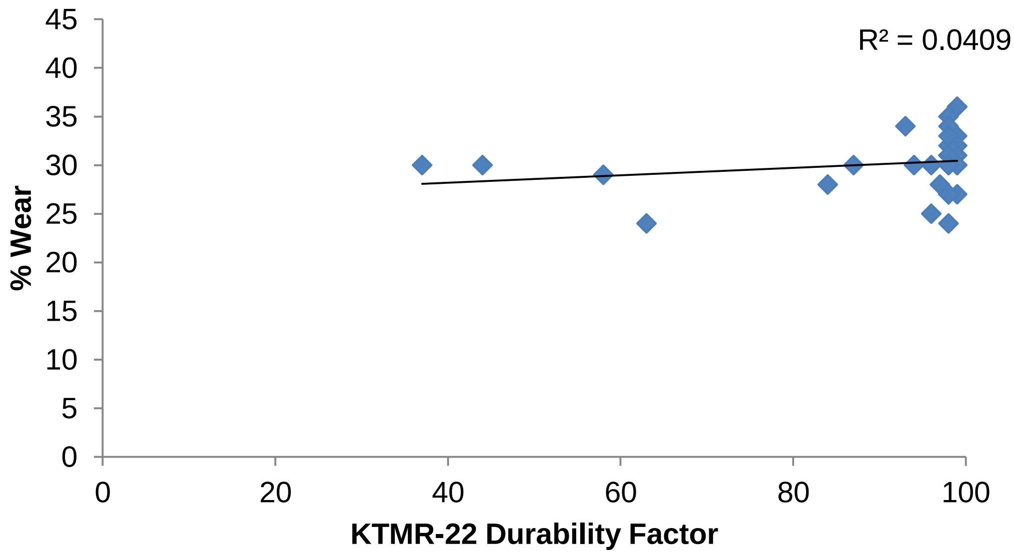

FIGURE 4.18
Wear versus KTMR-22 DF for KDOT Aggregates

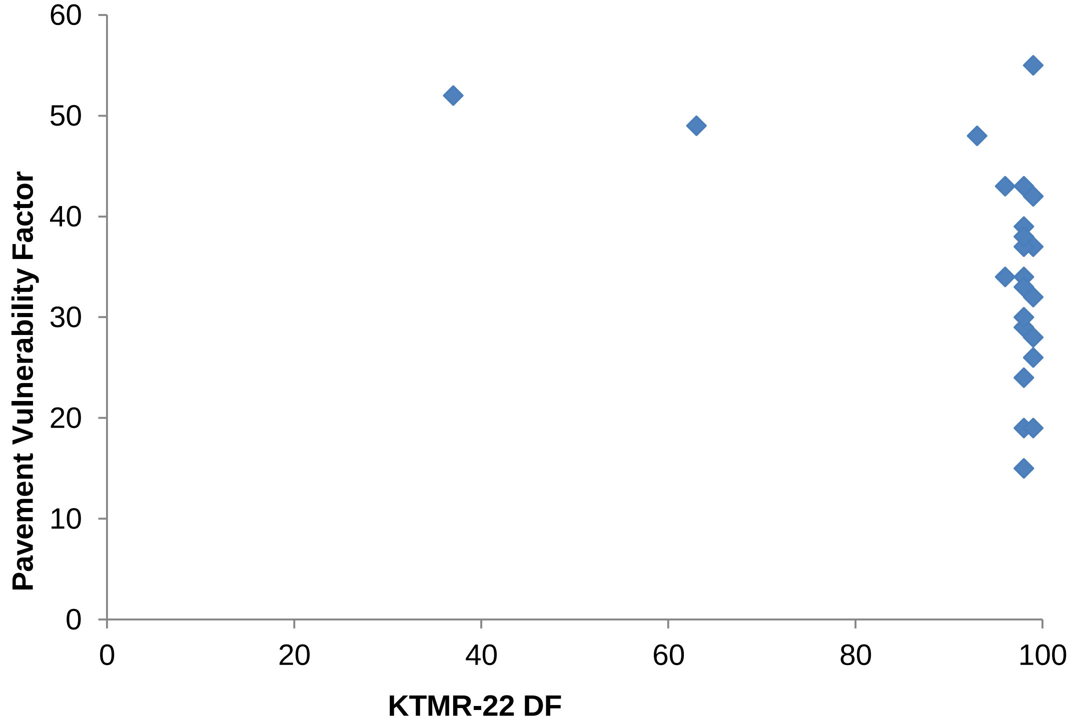

FIGURE 4.19
PVF versus KTMR-22 DF for KDOT Aggregates

Chapter 5: Conclusions and Implementation

5.1 Conclusions

The objective of this project was to determine if non-durable Kansas limestone aggregates could be identified using the CSA A23.2-24A test. In this method, aggregates were exposed to 3% NaCl solution and subjected to five unconfined freezing and thawing cycles. After this process, the aggregates were re-sieved with the mass loss on each aggregate size measured. With the aid of Canadian reference aggregates, a new locally available limestone control aggregate was developed for testing alongside the aggregates. For the Canadian standard control aggregate, three minutes of sieving with KSU sieving equipment yielded similar results as that obtained by MTO, giving confidence in the KSU methodology.

A version of CSA A23.2-24A modified to allow for smaller aggregate sizes was used for Kansas aggregates with size fractions between 1/4 and 3/4 inch which are typically used in Kansas. Thirty-nine aggregate samples were tested using this modified test. Twelve aggregates from the same quarries as used in the modified test method were tested in the CSA A23.2-23A test method using the 1/4 to 1 1/2 inches size fractions. A comparison of the freeze-thaw loss of the aggregates from 1/4 to 1 1/2 inches to the mass loss for the modified version of the CSA A23.2-24A test method showed that the exclusion of the large size fractions from the testing did not significantly alter the aggregate mass loss. To confirm if the Kansas limestone aggregates are sensitive to alternative salt solutions, the CSA A23.2-24A method was modified using 3% of $CaCl_2$ and 3% of $MgCl_2$ salt solutions and used on a subset of the aggregates. The $MgCl_2$ gave results similar to when the NaCl was used. The use of $CaCl_2$ consistently resulted in a decrease in freeze-thaw loss (%). No relationship between the CSA A23.2-24A test method results and the currently used KDOT performance tests was seen in the test results. The only relationship that could be determined from comparing the results of the currently used test methods to each other was that all of the aggregates that performed poorly in the KTMR-22 concrete beam freezing and thawing test had a PVF greater than 40. Nitrogen adsorption testing done on selected aggregates concluded that there was no correlation between aggregate surface area and freeze-thaw performance.

5.2 Implementation Recommendations

The conclusion obtained from this project has led to the following recommendation for implementation:

All of the aggregates tested in this study experienced relatively high mass losses in the CSA A23.2-24A test method. This indicates that salts can have a large negative influence on the freeze-thaw resistance of Kansas limestone aggregates. This may also help explain why some of the aggregates perform well in performance tests that are conducted without salts, but show distress in pavements. Future study on using CSA A23.2-24A method on Kansas aggregates should focus on the role of salts in concrete freeze-thaw damage.

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Appendix A: CSA A23.2-24A Tests on Samples Containing 1/4–1 1/2 Inch Aggregates

TABLE A.1
CSA A23.2-24A Test Results for 1 1/2–1 Inch Sieve Fraction

KDOT Lab ID	BED	Weight Loss (%) on 1 1/2–1 Inch Sieve				
		1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1468-P	8	13.79	14.78	16.10	16.34	16.50
09-1468-P	9	13.52	14.17	15.76	16.05	16.83
09-1469-P	1	13.30	14.44	16.50	16.71	17.14
09-1469-P	2	15.39	16.88	18.40	18.78	19.00
09-1884	1	16.32	16.97	19.76	20.05	20.23
09-1884	3	16.70	17.44	19.00	19.31	19.59
09-1885	1	15.39	16.88	18.40	18.78	19.00
09-1939	-	16.32	16.97	19.76	20.05	20.23
09-1940	-	16.70	17.44	19.00	19.31	19.59
09-3051	2	16.58	17.28	18.20	18.58	18.82
09-3051	3	16.00	16.31	18.87	19.40	19.78
09-1474	1	15.60	16.04	18.00	18.45	18.75

TABLE A.2
CSA A23.2-24A Test Results for 1–3/4 Inch Sieve Fraction

KDOT Lab ID	BED	Weight Loss (%) on 1–¾ Inch Sieve				
		1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1468-P	8	13.67	14.66	16.18	16.34	16.50
09-1468-P	9	13.52	14.17	15.76	16.05	16.83
09-1469-P	1	13.30	14.36	16.3	16.71	17.02
09-1469-P	2	15.19	14.86	18.	19.14	19.70
09-1884	1	15.72	16.37	18.18	18.85	19.23
09-1884	3	15.18	16.14	19.18	19.91	20.14
09-1885	1	15.19	14.88	18.50	19.14	19.70
09-1939	-	15.72	16.37	18.16	18.85	19.23
09-1940	-	15.18	16.16	19.18	19.91	20.14
09-3051	2	14.99	15.30	18.06	18.45	18.92
09-3051	3	15.32	15.73	17.72	18.40	18.83
09-1474	1	14.37	15.01	18.78	19.02	19.37

TABLE A.3
CSA A23.2-24A Test Results on 3/4–1/2 Inch Sieve Fraction

KDOT Lab ID	BED	Weight Loss (%) on 3/4–1/2 Inch Sieve				
		1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1468-P	8	13.95	14.88	16.24	16.55	16.76
09-1468-P	9	13.52	14.48	16.00	16.4	16.88
09-1469-P	1	13.30	14.68	16.50	16.71	17.14
09-1469-P	2	14.78	16.90	19.39	20.15	20.31
09-1884	1	15.52	16.48	18.00	19.20	20
09-1884	3	14.74	15.48	17.54	18.31	19.94
09-1885	1	14.78	16.90	19.39	20.15	20.31
09-1939	-	15.52	16.48	18.00	19.2	20
09-1940	-	14.74	15.48	17.54	18.31	19.94
09-3051	2	14.94	16.69	17.79	18.6	19.28
09-3051	3	15.83	16.21	17.62	18.4	18.68
09-1474	1	14.57	15.60	17.14	17.8	18.2

TABLE A.4
CSA A23.2-24A Test Results on 1/2–3/8 Inch Sieve Fraction

KDOT Lab ID	BED	Weight Loss (%) on 1/2–3/8 Inch Sieve				
		1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1468-P	8	13.78	14.66	16.18	16.97	17.11
09-1468-P	9	12.48	13.47	15.24	16.18	16.72
09-1469-P	1	12.46	13.72	16.27	17.25	18.11
09-1469-P	2	15.68	16.68	18.08	18.37	18.71
09-1884	1	16.68	17.47	18.44	18.18	18.52
09-1884	3	16.06	16.92	18.17	18.55	18.98
09-1885	1	15.68	16.68	18.08	18.37	18.71
09-1939	-	16.68	17.47	18.44	18.18	18.52
09-1940	-	16.06	16.92	18.17	18.55	18.98
09-3051	2	16.68	17.18	17.68	18.17	18.41
09-3051	3	17.18	17.53	17.99	18.26	18.5
09-1474	1	15.87	16.46	17.96	18.36	18.7

TABLE A.5
CSA A23.2-24A Test Results on 3/8–1/4 Inch Sieve Fraction

KDOT Lab ID	BED	Weight Loss (%) on 3/8–1/4 Inch Sieve				
		1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1468-P	8	14.32	14.66	15.92	16.96	17.3
09-1468-P	9	13.34	13.96	15.64	16.2	16.74
09-1469-P	1	13.44	14.46	16.86	17.52	17.92
09-1469-P	2	13.58	15.26	18.96	19.36	19.82
09-1884	1	15.06	15.98	18.34	18.84	19.74
09-1884	3	15.84	16.44	17.8	18.32	18.82
09-1885	1	13.58	15.26	18.96	19.36	19.82
09-1939	-	15.06	15.98	18.34	18.84	19.74
09-1940	-	15.84	16.44	17.8	18.32	18.82
09-3051	2	14.44	15.46	16.96	18.36	19.02
09-3051	3	14.74	15.58	17.54	19.3	19.82
09-1474	1	13.98	14.24	15.74	16.92	17.82

TABLE A.6
Average Weighted Freeze-Thaw Loss for Samples from 1/4–1 1/2 Inch Aggregates Using CSA A23.2-24A Method

KDOT Lab ID	BED	Average Weighted Freeze-Thaw Loss				
		1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1468-P	8	13.90	14.73	16.12	16.64	16.84
09-1468-P	9	13.28	14.05	15.68	16.18	16.80
09-1469-P	1	13.16	14.33	16.50	16.98	17.47
09-1469-P	2	14.93	16.12	18.67	19.16	19.51
09-1884	1	15.86	16.66	18.54	19.02	19.55
09-1884	3	15.71	16.49	18.34	18.88	19.50
09-1885	1	14.93	16.12	18.67	19.16	19.51
09-1939	-	15.86	16.66	18.54	19.02	19.55
09-1940	-	15.71	16.49	18.34	18.88	19.50
09-3051	2	15.53	16.39	17.74	18.44	18.89
09-3051	3	15.82	16.27	17.95	18.75	19.12
09-1474	1	14.88	15.47	17.52	18.11	18.57

Appendix B: CSA A23.2-24A Tests on Samples Containing 1/4–3/4 Inch Aggregates

TABLE B1
CSA A23.2-24A Test Results on 3/4–1/2 Inch Sieve Fraction

KDOT Lab ID	BED	MF Sample ID	Quarry No.	Weight Loss (%) on 3/4–1/2 Inch Sieve				
				1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1008	1-3	746348	4-063-02	12.36	13.20	15.20	15.64	16.01
09-1010	1-3	746354	4-025-02	14.18	15.16	17.20	17.71	18.03
09-1227	1-5	747555	4-063-05	10.45	11.70	13.34	14.17	14.50
09-1228	1-2	747556	4-050-06	11.71	12.50	14.08	14.75	15.18
09-1231	1-4	748251	4-011-01	13.93	14.66	16.19	16.75	17.00
09-1248	4-5	749369	4-030-02	12.10	12.84	14.39	14.84	15.03
09-1257	1	749653	4-061-10	15.60	16.35	17.92	18.45	18.84
09-1430	1-2	750458	4-006-14	11.61	12.40	13.98	14.59	15.09
09-1454	1	751122	4-061-10	15.92	16.52	18.42	19.12	19.58
09-1706	2-6	753423	4-002-01	12.36	13.20	15.20	15.64	16.01
09-1917	5-7	755203	1-045-11	15.59	16.04	18.00	18.51	18.84
09-1918	4-5	755317	4-030-02	14.04	14.55	16.33	16.99	17.33
09-1475	1			13.12	13.82	15.60	16.17	16.51
09-2257	1	757664						
09-2102	4	756719	4-030-02					
09-3497				15.17	16.14	18.01	18.70	19.17
09-3645				13.96	14.94	16.59	17.07	17.70
09-2943	5-7	765280	1-046-11	13.28	14.69	16.42	17.01	17.19
09-2788	4-5	763711	4-030-02	11.57	12.42	13.78	14.42	14.81
09-3453	3		4-061-09	12.86	13.76	14.90	15.63	16.10
10-0354	C,D		5-018-01	14.51	15.34	16.04	16.42	16.86

TABLE B.1, Continued

KDOT Lab ID	BED	MF Sample ID	Quarry No.	Weight Loss (%) on 3/4–1/2 Inch Sieve				
				1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
08-2058	1		MO-042	14.05	14.54	15.95	16.58	16.90
09-2642	2	803903	1-046-16	12.58	13.22	14.67	15.21	15.70
09-3453	4	804008	4-061-09	14.53	15.25	15.99	16.45	16.75
08-355				13.38	14.05	15.20	15.69	16.06
08-2323				12.90	13.50	14.05	14.50	14.84
09-2642	1	803903	1-046-16	14.82	15.43	16.18	16.57	16.87
10-0211	2,3	802439	MO-023					
10-0424	1,2,3	802244	4-025-02					

TABLE B.2
CSA A23.2-24A Test Results Obtained on 1/2–3/8 Inch Sieve Fraction

KDOT Lab ID	BED	MF Sample ID	Quarry No.	Weight Loss (%) on 1/2–3/8 Inch Sieve				
				1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1008	1-3	746348	4-063-02	13.11	13.75	15.24	15.89	16.50
09-1010	1-3	746354	4-025-02	14.53	15.07	17.10	17.64	18.01
09-1227	1-5	747555	4-063-05	11.69	12.29	13.50	13.97	14.54
09-1228	1-2	747556	4-050-06	12.00	12.44	14.10	14.50	15.01
09-1231	1-4	748251	4-011-01	13.61	14.31	16.07	16.79	17.44
09-1248	4-5	749369	4-030-02	12.57	13.55	15.56	16.24	16.58
09-1257	1	749653	4-061-10	14.50	15.58	18.00	18.60	19.29
09-1430	1-2	750458	4-006-14	12.39	12.95	14.79	15.24	15.70
09-1454	1	751122	4-061-10	15.29	16.14	18.12	18.51	18.94
09-1706	2-6	753423	4-002-01	12.97	13.60	15.10	15.56	15.94
09-1917	5-7	755203	1-045-11	14.50	15.08	17.59	18.38	18.71
09-1918	4-5	755317	4-030-02	13.97	14.94	16.60	17.11	17.44
09-1475	1			13.30	13.84	15.80	16.25	16.60
09-2257	1	757664		14.36	14.90	15.90	16.25	16.47
09-2102	4	756719	4-030-02	14.79	15.30	16.34	16.72	16.95
09-3497				15.00	15.81	17.56	17.93	18.13
09-3645				13.44	13.44	13.44	13.44	13.44
09-2943	5-7	765280	1-046-11	13.78	14.39	16.25	16.94	17.20
09-2788	4-5	763711	4-030-02	12.24	13.00	14.36	14.87	15.22
09-3453	3		4-061-09	13.32	14.48	15.43	15.97	16.49
10-0354	C,D		5-018-01	14.25	14.80	15.67	16.29	16.53
08-2058	1		MO-042	13.78	14.38	15.24	16.30	16.59

TABLE B.2, Continued

KDOT Lab ID	BED	MF Sample ID	Quarry No.	Weight Loss (%) on 1/2–3/8 Inch Sieve				
				1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-2642	2	803903	1-046-16	13.04	13.51	14.23	14.82	15.32
09-3453	4	804008	4-061-09	14.31	14.87	15.92	16.25	16.44
08-355				12.88	13.76	14.63	15.12	15.52
08-2323				13.24	13.93	14.59	15.07	15.41
09-2642	1	803903	1-046-16	14.47	15.07	15.74	16.08	16.28
10-0211	2,3	802439	MO-023	13.50	14.23	15.075	15.62	16.06
10-0424	1,2,3	802244	4-025-02	14.70	15.38	15.88	16.23	16.47

TABLE B.3
CSA A23.2-24A Test Results Obtained on 3/8–1/4 Inch Sieve Fraction

KDOT Lab ID	BED	MF Sample ID	Quarry No.	Weight Loss (%) on 3/8–1/4 Inch Sieve				
				1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1008	1-3	746348	4-063-02	12.78	13.93	15.5	16.06	16.89
09-1010	1-3	746354	4-025-02	14.14	15.43	17.21	18.17	19.29
09-1227	1-5	747555	4-063-05	11.25	12.07	13.42	14.21	15.03
09-1228	1-2	747556	4-050-06	11.47	12.26	14.27	15.71	16.13
09-1231	1-4	748251	4-011-01	13.75	14.62	16.34	17.57	18.19
09-1248	4-5	749369	4-030-02	12.07	13.03	15.09	15.87	16.21
09-1257	1	749653	4-061-10	15.96	16.79	18.12	18.81	19.52
09-1430	1-2	750458	4-006-14	13.24	13.85	15.29	16.12	16.83
09-1454	1	751122	4-061-10	15.63	16.11	17.82	18.41	18.93
09-1706	2-6	753423	4-002-01	12.23	12.79	14.76	15.12	15.68
09-1917	5-7	755203	1-045-11	14.93	15.78	17.42	17.91	18.26
09-1918	4-5	755317	4-030-02	13.95	14.57	16.42	16.86	17.24
09-1475	1			13.02	13.79	15.78	16.19	16.53
09-2257	1	757664		15.21	15.86	17.44	18.09	18.47
09-2102	4	756719	4-030-02	14.11	14.78	16.90	17.93	18.36
09-3497								
09-3645								
09-2943	5-7	765280	1-046-11					
09-2788	4-5	763711	4-030-02					
09-3453	3		4-061-09	12.36	13.44	14.44	15.22	15.86
10-0354	C,D		5-018-01	14.77	15.61	16.34	16.76	17.10
08-2058	1		MO-042	13.64	14.27	15.32	16.08	16.51
09-2642	2	803903	1-046-16	13.08	13.72	14.92	15.45	16.03

TABLE B.3, Continued

KDOT Lab ID	BED	MF Sample ID	Quarry No.	Weight Loss (%) on 3/8–1/4 Inch Sieve				
				1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-3453	4	804008	4-061-09	14.87	15.18	15.70	15.99	16.14
08-355				13.21	13.93	14.81	15.85	16.30
08-2323				13.51	13.91	14.38	15.00	15.45
09-2642	1	803903	1-046-16	14.99	15.66	16.44	16.75	17.05
10-0211	2,3	802439	MO-023					
10-0424	1,2,3	802244	4-025-02	12.58	13.79	14.46	15.12	15.53

TABLE B.4
Average Weighted Freeze-Thaw Loss for Samples Using CSA A23.2-24A Method

KDOT Lab ID	BED	MF Sample ID	Quarry No.	Average Weighted Freeze-Thaw Loss				
				1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1008	1-3	746348	4-063-02	12.75	13.63	15.31	15.86	16.47
09-1010	1-3	746354	4-025-02	14.28	15.22	17.17	17.84	18.44
09-1227	1-5	747555	4-063-05	11.13	12.02	13.42	14.12	14.69
09-1228	1-2	747556	4-050-06	11.72	12.40	14.15	14.99	15.44
09-1231	1-4	748251	4-011-01	13.76	14.53	16.20	17.03	17.54
09-1248	4-5	749369	4-030-02	12.25	13.14	15.01	15.65	15.94
09-1257	1	749653	4-061-10	15.35	16.24	18.01	18.62	19.21
09-1430	1-2	750458	4-006-14	12.41	13.06	14.69	15.32	15.87
09-1454	1	751122	4-061-10	15.61	16.26	18.12	18.68	19.15
09-1706	2-6	753423	4-002-01	12.52	13.20	15.02	15.44	15.88
09-1917	5-7	755203	1-045-11	15.01	15.63	17.67	18.27	18.60
09-1918	4-5	755317	4-030-02	13.99	14.69	16.45	16.98	17.34
09-1475	1			13.15	13.82	15.73	16.20	16.54
09-2257	1	757664		14.78	15.38	16.67	17.17	17.47
09-2102	4	756719	4-030-02	14.45	15.04	16.62	17.33	17.66
09-3497				15.09	15.97	17.78	18.32	18.65
09-3645				13.70	14.19	15.01	15.25	15.57
09-2943	5-7	765280	1-046-11	13.53	14.54	16.34	16.98	17.19
09-2788	4-5	763711	4-030-02	11.91	12.71	14.07	14.64	15.02
09-3453	3		4-061-09	12.84	13.89	14.92	15.60	16.15
10-0354	C,D		5-018-01	14.51	15.25	16.01	16.49	16.83
08-2058	1		MO-042	13.82	14.39	15.50	16.32	16.66
09-2642	2	803903	1-046-16	12.90	13.48	14.60	15.16	15.68
09-3453	4	804008	4-061-09	14.57	15.10	15.87	16.23	16.44

TABLE B.3, Continued

KDOT Lab ID	BED	MF Sample ID	Quarry No.	Average Weighted Freeze-Thaw Loss				
				1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
08-355				13.16	13.91	14.88	15.55	15.96
08-2323				13.21	13.78	14.34	14.85	15.23
09-2642	1	803903	1-046-16	14.64	15.253	15.96	16.33	16.57
10-0211	2,3	802439	MO-023	13.50	14.23	15.07	15.62	16.06
10-0424	1,2,3	802244	4-025-02	13.64	14.58	15.17	15.67	16.00

Appendix C: Modified CSA A23.2-24A Tests Results Using $MgCl_2$ and $CaCl_2$ Salt Solutions

TABLE C.1
Average Weighted Freeze-Thaw Loss for Samples Containing 1/4–3/4 Inch Aggregates by Using $CaCl_2$ Salt Solution Method

KDOT Lab ID	BED	MF Sample ID	Quarry No.	Average Weighted Freeze-Thaw Loss (%)				
				1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1008	1-3	746348	4-063-02	10.65	11.55	13.47	14.18	14.68
09-1010	1-3	746354	4-025-02	12.877	13.81	15.39	16.24	16.56
09-1248	4-5	749369	4-030-02	10.76	11.50	13.00	13.73	14.04
09-1454	1	751122	4-061-10	13.92	14.74	16.07	16.70	16.93
09-1918	4-5	755317	4-030-02	11.78	12.49	14.341	15.18	15.58
09-1706	2-6	753423	4-002-01	10.31	11.149	12.81	13.46	13.94
09-1257	1	749653	4-061-10	12.59	13.36	15.29	16.05	16.50

TABLE C.2
Average Weighted Freeze-Thaw Loss for Samples Containing 1/4–1 1/2 Inch Aggregates by Using $MgCl_2$ Salt Solution Method

KDOT Lab ID	BED	Average Weighted Freeze-Thaw Loss (%)				
		1 Min.	2 Min.	3 Min.	4 Min.	5 Min.
09-1468-P	8	14.130	15.23	17.28	17.79	18.14
09-1468-P	9	12.58	14.08	16.11	16.90	17.39
09-1469-P	1	12.00	13.23	15.27	16.17	16.72
09-1469-P	2	16.12	16.82	18.23	18.72	19.03
09-1884	1	16.68	17.35	18.46	18.79	19.02
09-1885	1	16.30	16.98	18.12	18.68	18.84
09-1939		16.55	17.21	18.32	18.85	19.07
09-1940		16.62	17.13	18.21	18.55	18.85
09-3051	2	16.127	16.58	17.94	18.30	18.66

Appendix D: Results from KDOT Tests on Companion Aggregates

TABLE D.1
KDOT Results on Samples Containing 1/4–1 1/2 Inch Aggregates

KDOT Lab ID	BED	DF	EXP	MOD FT	%A.I	%WEAR	CY	PVF
09-1468-P	8	63	0.116	0.98	3.23	24		49
09-1468-P	9	37	0.181	0.93	7.92	30		52
09-1469-P	1	99	0.012	0.97	4.51	27		55
09-1469-P	2	99	0.009	0.94	5.42	30		42
09-1884	1	98	0.01	0.97	2.52	31		34
09-1884	3	98	0.009	0.86	5.59	30		43
09-1885	1	96	0.017	0.97	2.38	25		34
09-1939								
09-1940								
09-3051	2			0.98	1.06	35	300	12
09-3051	3			0.95	3.03	39	300	28
09-1474	1	98	0.002	0.99	1.52	27	300	24

TABLE D.2
KDOT Results on Samples Containing 1/4–3/4 Inch Aggregates

KDOT Lab ID	BED	DF	EXP	MOD FT	%A.I	%WEAR	CY	PVF
09-1008	1-3	99	0.008	0.95	4.50	36	300	32
09-1010	1-3	99	0.008	0.98	4.80	33	300	42
09-1227	1-5	93	0.028	0.96	4.7	34	300	48
09-1228	1-2	99	0.015	0.99	2.8	32	300	37
09-1231	1-4	98	0.012	0.98	1.7	35	300	19
09-1248	4-5	99	0	0.96	3.7	36	300	28
09-1257	1	98	0.01	0.98	2.3	27	300	37
09-1430	1-2	99	0.008	0.98	1.7	31	300	26
09-1454	1	98	0.008	0.97	1.8	27	300	29
09-1706	2-6	96	0.004	0.96	6.3	30	300	43
09-1917	5-7	98	0.012	0.99	1.2	31	300	15
09-1918	4-5	98	0.014	0.95	3.8	34	300	30
09-1475	1	98	0.018	0.99	2	24	300	39
09-2257	1	97	0.018	0.98	1.95	27	300	32
09-2102	4	98	0.007	0.98	3.8	32	300	33
09-3497		98	0.07	0.99	1.38	34	300	19
09-3645								
09-2943	5-7	99	0.001	0.98	1.4	30	300	19
09-2788	4-5	98	0.004	0.98	4.9	33	300	38
09-3453	3	94	0.014	0.94	6.23	30	300	16
10-0354	C,D	97	0.09	0.89	24.85	28	300	74
08-2058	1	87	0.032	0.9	10.32	30	300	56
09-2642	2	84	0.045	0.97	4.14	28	237	52
09-3453	4	44	0.127	0.85	8.67	30	300	56
08-355		63	0.12	0.98	3.23	24	300	49
08-2323		99	0.01	0.78	5.30	30	300	41
09-2642	1	58	0.082	0.9	6.81	29	237	52
10-0211	2,3	86	0.047	0.93	5.90	26	300	59
10-0424	1,2,3	98	0.008	0.95	3.39	32	300	32

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