The Effect of Minnesota Aggregates on Rapid Chloride Permeability Tests

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16. Abstract (Limit: 200 words)

This report investigates the effect of the type of coarse aggregate used in concrete on chloride ions penetrability as indicated by the rapid chloride penetration test (RCPT). Twelve coarse aggregate types, commonly used in Minnesota Department of Transportation highway construction projects, were identified and used for this study. The coarse aggregate types were subjected to laboratory testing to determine their physical properties and ambient chloride content. The aggregate types were used to prepare fresh concrete according to Mn/DOT specifications in which silica fume and fly ash were used. In order to characterize the concrete in terms of resistance to chloride ions penetration, concrete specimens made of these aggregate types were subjected to the rapid chloride permeability test at different ages. All mix parameters including gradation and quantities of different aggregates were held constant in different mixes. The only variable was the aggregate type. For concrete specimens tested at 28 days of age, the average total charge passed varied between 1,452 and 2,606 Coulombs, which can be described as "low" to "moderate" chloride ions penetrability, according to AASHTO designation. The average total charge passed decreased with time (age) for all of the concrete specimens tested. Considering specimens at 91 days of age, the average total charge passed ranged from 601 to 1,236 Coulombs, which can be characterized as "very low" to "low" chloride ions penetrability. The aggregate type has a noticeable influence on the RCPT results for the concrete mix design that was utilized.

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The Effect of Minnesota Aggregates on Rapid Chloride Permeability Tests

Final Report

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Executive Summary

In Minnesota and other northern states, deicing agents are commonly applied to roadway pavements and bridge decks during snowstorms and freezing temperatures. The most commonly used deicing agent is Sodium Chloride NaCl (salt). Chloride ions derived from the salt solution will penetrate and eventually reach into the vicinity of the reinforcing steel in bridge decks, destroying the passive environment provided to the reinforcing steel by the high alkalinity of the concrete. Therefore, chloride ions are one of the primary factors in corrosion of reinforcing steel, which is sustained by the presence of moisture and oxygen. These conditions could cause early deterioration of bridge decks and result in very costly rehabilitation.

This research investigated the effect of the type of coarse aggregate used in concrete on resistance to the penetration of chloride ions as indicated by the rapid chloride permeability test. The RCPT is a standard test adopted by AASHTO and ASTM and is known as AASHTO T 277 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration."

Twelve coarse aggregate types, commonly used in Mn/DOT highway construction projects, were identified and used for this study. The coarse aggregate types were subjected to laboratory testing to determine their physical properties and then used to prepare fresh concrete according to Mn/DOT specifications in which silica fume and fly ash were used. In order to characterize the concrete in terms of resistance to chloride ions penetration, concrete specimens were made of these aggregate types and were subjected to the rapid chloride permeability test at different ages; namely 28, 56, and 91 days. All mix parameters including gradation and quantities of different aggregates were held constant in different mixes. The only variable was the aggregate type. Coarse and fine aggregates were selected and shipped to UWM by Mn/DOT project research committee.

For each aggregate type, the RCPT was performed on three specimens that were prepared from three different trial mixes. For concrete specimens tested at 28 days of age, the average total charge passed varied between 1,452 and 2,606 Coulombs, which can be described as "low" to "moderate" chloride ions penetrability, according to AASHTO T 277 designation. The "moderate" description was obtained as a result of RCPT on concrete specimens made of crushed limestone aggregate from Ulland, Goldberg, Kraemer, and Larson pit. Concrete specimens made of Michigan limestone were characterized as of "low" chloride ions penetrability according to AASHTO interpretation of RCPT results. For concrete made of crushed aggregates of igneous and metamorphic rock origin (Brielmaier, Martin Marietta, and New Ulm), all specimens were characterized as of "low" chloride ions penetrability. The concrete specimens made of aggregate that were mixture of crushed and smooth round particles of igneous rock origin were characterized as "moderate" chloride ions penetrability for Barton aggregate, and "low" chloride ion penetrability for Fischer, Mark, and Lanthier aggregates.

For all concrete specimens tested, the total charge passed decreased with time (concrete age). For example, Michigan limestone concrete specimens from trial mix #1 showed a decrease in the total charge passed from 1,878 Coulombs at age of 28 days to 732 Coulombs at age of 91 days. This is a reduction of about 61% in the initial total charge passed in approximately two months. The reason for this reduction is believed to be the continuous hydration of the cement. This

reaction results in reducing the pore space and pore connectivity inside the concrete and therefore the penetration of chloride ions.

Considering all specimens at 91 days of age, the average total charge passed ranged from 601 to 1,236 Coulombs, which can be characterized as "very low" to "low" chloride ions penetrability. At age of 91 days, concrete specimens made of limestone aggregates from Kraemer and Larson pit were described as "low" chloride ions penetrability according to the AASHTO T 277 designation. Concrete specimens made of all other aggregate types were classified as "very low" chloride ions penetrability.

This research provided analyses of the RCPT results as described by AASTHO and ASTM. The characterization of the concrete made of the aggregate types used was made based on the results of the standard test procedure of AASHTO T 277.

Chapter 1
Introduction

 In Minnesota and other northern states, deicing agents are commonly applied to roadway pavements and bridge decks during snowstorms and freezing temperatures. The most commonly used deicing agent is Sodium Chloride NaCl (salt). Chloride ions derived from the salt solution will penetrate and eventually reach into the vicinity of the reinforcing steel in bridge decks, destroying the passive environment provided to the reinforcing steel by the high alkalinity of the concrete. Therefore, chloride ions are one of the primary factors in corrosion of reinforcing steel, which is sustained by the presence of moisture and oxygen. These conditions could cause early deterioration of bridge decks and result in very costly rehabilitation.

This report presents the results of a research effort to investigate the effect of the type of coarse aggregate used in concrete on resistance to the penetration of chloride ions as indicated by the rapid chloride permeability test (RCPT). The RCPT is a standard test adopted by the American Association of State Highway and Transportation Officials (AASHTO). The test is known as AASHTO T 277: Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. Coarse aggregates from 12 different sources were identified by Minnesota Department of Transportation (Mn/DOT) project research team. These aggregate types are commonly used in Mn/DOT highway construction projects. The coarse aggregate types were subjected to laboratory testing program to determine their physical properties and ambient chloride content. The aggregate types were used to prepare fresh concrete according to Mn/DOT specifications. Concrete specimens made of these aggregate types were subjected to the rapid chloride permeability test at different ages.

This research report is organized in six chapters. Chapter 1 introduces the problem and the goal of the research project. Literature review on the ingress of chloride ions and methods of characterization are discussed in detail in Chapter 2. Results of the laboratory tests to characterize the aggregates used in this study are presented in Chapter 3. Chapter 4 describes the work done to prepare fresh concrete and to cast concrete cylinders. Results of the RCPT on the concrete specimens at different ages with detailed analysis are presented in Chapter 5. Finally, the conclusions are presented in Chapter 6.

Chapter 2
Literature Review

Many reinforced concrete bridge structures are subjected to harsh environments and as a result are susceptible to early deterioration. Investigations (e.g., PCA 1970, Spellman & Stratfull 1970) have shown that the most predominant cause of early deterioration of reinforced concrete bridge components such as bridge decks is the corrosion of the reinforcing steel. In regions where deicing salts are applied to the road surface during winter, corrosion of reinforcing steel is mainly attributed to the presence of chloride ions derived from salts. Chloride ions penetrate the concrete and destroy the passive environment provided to the reinforcing steel by the high alkalinity of the concrete. The presence of moisture and oxygen is vital to initiate and continue the corrosion of reinforcing steel. Corrosion of the reinforcing steel results in the formation of rust products on the surface of the reinforcing steel. These rust products have two to four times the original volume of the reinforcing steel. This expansion induces tensile stresses in the surrounding concrete and will cause the concrete to crack. It is evident that the penetration of chloride ions into the reinforced concrete leads to concrete cracking and spalling causing loss of serviceability and subsequently reduction in strength and safety of structures (Rasheeduzzafar et al. 1992).

Transport Mechanisms of Chloride Ions

The chloride ions penetration of reinforced concrete is the major cause of the corrosion of reinforcing steel. It is essential to understand the transport mechanisms in which the chloride ions penetrate concrete masses and the factors affecting their penetration. Chloride ions penetrate concrete mass through three main mechanisms: diffusion, hydrostatic pressure, and capillary absorption. However, the predominant transport mechanism of chloride ions is the diffusion through the pore fluid (Collepardi et al. 1972, Feldman et al. 1993). Diffusion is defined as the ionic movement under a concentration gradient. Fick's First Law defines the one-dimensional ionic diffusion as follows:

$$J = -D_{eff} \frac{dC}{dx}$$

(1)

where, J is the flux of chloride ions, D_{eff} is the effective diffusion coefficient, C is the concentration of chloride ions, and x is the position variable. The flux is defined as the quantity of chloride ions that pass a unit surface area per unit of time. Fick's First Law is valid only for steady-state conditions. When the ionic concentration vary with time (non-steady conditions), the ionic diffusion is described by Fick's Second law as follows:

$$\frac{\partial C}{\partial t} = D_{eff} \frac{\partial^2 C}{\partial x^2}$$

(2)

Diffusion of chloride ions in concrete masses requires the presence of two elements: continuous pore fluid medium and ion concentration gradient. Concrete is a porous medium made of solid parts and voids that are filled with fluid and/or air. The main component of ionic diffusion is through the pore fluid. Diffusion through the solid part of the concrete is negligible (Stanish et al. 1997). Therefore, the presence of fluid (water) is essential to the diffusion of chloride ions.

In addition, chloride ions can penetrate concrete masses under hydraulic pressure. This transport mechanism requires that chloride ions are present at the concrete surface and are subjected to a hydraulic pressure. Chloride ions will penetrate the concrete mass under the applied hydraulic head. This mechanism is not common in highway structures such as bridges (Stanish et al. 1997).

The third transport mechanism of chloride ions into concrete is through the capillary absorption. This mechanism requires moisture gradient in order for chloride ions to penetrate concrete masses. Chloride ions in the water enter concrete pores through capillary suction that takes place when water encounters a dry concrete surface. Capillary suction usually occurs at shallow depths where chloride ions generally do not reach the vicinity of the reinforcing steel. This phenomenon may not transport chloride ions into the vicinity of the reinforcing steel, but will reduce the distance that chloride ions need to diffuse to reach the vicinity of the reinforcing steel (Thomas et al. 1995).

Corrosion of Reinforcing Steel

When concrete is poured around reinforcing steel, a passive protective layer is formed on the surface of the steel. The protective layer is formed as a result of a chemical reaction between the plastic concrete and the reinforcing steel (Slag Cement Association 2002).

When reinforced concrete is exposed to salt environment, chloride ions move toward the reinforcing steel through the small pores within the concrete matrix. As time passes, chloride ions reach the vicinity of the reinforcing steel and initiate a chemical reaction that breaks down the protective layer leading to steel corrosion. Corrosion of reinforcing steel occurs in the presence of moisture and oxygen. According to the American Society for Testing and Materials (ASTM), corrosion is defined as "the chemical or electrochemical reaction between a material, usually metal, and its environment that produces a deterioration of the material and its properties." Corrosion of reinforcing steel produces rust products with volumes that are two to four times the original volume of the steel. This volume change (expansion) leads to concrete cracking and spalling. Thus, corrosion is one of the primary causes of the deterioration of both the concrete and reinforcing steel and could greatly compromise the structural integrity as a whole.

Test Methods to Determine Ingress of Chloride Ions

The most common method used to assess the chloride ion ingress into concrete is the rapid chloride permeability test. Some of the chloride ions penetrability test methods require months of sample conditioning and testing, while others can be performed in relatively short time. The common tests are generally categorized based on the test duration as long-term or short-term. Stanish et al. (1997) presented a summary of common chloride ions penetration tests as shown in Table 2.1.

Table 2.1: Summary of the chloride ions penetration test methods (Stanish et al. 1997)

Test Method		Considers Chloride Ion Movement	At a Constant Temperature	Unaffected by Conductors in the Concrete	Approximate Duration of Test Procedure
Long Term	AASHTO T259 (salt ponding)	Yes	Yes	Yes	90 day after curing and conditioning
	Bulk Diffusion (Nordtest)	Yes	Yes	Yes	40 – 120 days after curing and conditioning
Short Term	RCPT (AASHTO T 277)	No	No	No	6 hours
	Electrical Migration	Yes	Yes	No	Depends on voltage and concrete
	Rapid Migration (CTH)	Yes	Yes	No	8 hours
	Resistivity	No	Yes	No	30 minutes
	Pressure Penetration	Yes	Yes	Yes	Depends on pressure and concrete (but potentially long)
Other	Sorptivity – Lab	No	Yes	Yes	1 week including conditioning
	Sorptivity – Field	No	Yes	Yes	30 minutes
	Propan-2-ol Counter Diffusion	No	Yes	Yes	13 days with thin paste samples
	Gas Diffusion	No	Yes	Yes	2 – 3 hours

Rapid Chloride Permeability Test

Recognizing the detrimental effects of the chloride ions on the reinforced concrete structures, research efforts have focused on development of test methods to rapidly determine the resistance of various concretes to ingress of chloride ions. Whiting (1981) developed the rapid chloride permeability test under research sponsored by the Federal Highway Administration (FHWA). The test was adopted by AASHTO in 1983 and was given the designation AASHTO T 277. In 1991, this test was adopted by ASTM and was given the designation ASTM C 1202. The AASHTO T 277: Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration is referred to as the rapid chloride permeability test.

Figure 2.1 shows a picture of the RCPT setup at the University of Wisconsin – Milwaukee. In this test method, a water saturated concrete cylindrical specimen (thickness = 2.0″ and diameter = 4.0″) is subjected to a DC voltage of 60 V across its thickness for a period of 6 hours. The concrete specimen is mounted on the voltage cell with one side immersed in a sodium chloride solution (3% NaCl) and the other side in a sodium hydroxide solution (0.3 N NaOH), as shown in Figure 2.2. The amount of the electrical current passing through the specimen is continuously

monitored. The total charge (in Coulombs) that passes through the concrete specimen is used to characterize the specimen's resistance to chloride ions penetration.

Table 2.2 presents the AASHTO qualitative ratings for concrete specimens based on the total amount of charge passed. Concrete specimens with a total passing charge of less than 100 Coulombs are considered to have "negligible" chloride ions penetrability. While concrete specimens with a total passing charge of more than 4,000 Coulombs are considered to have "high" chloride ions penetrability.

Figure 2.1: Rapid chloride permeability test setup at UWM

Figure 2.2: Concrete specimen mounted inside the RCPT cell.

As presented earlier, the AASHTO T 277 measures the total charge passing through a concrete specimen not the permeability. Permeability is defined as the ease of fluid movement under pressure gradient. Therefore, describing the AASHTO T 277 as a permeability test is technically not accurate.

Table 2.2: Characterization of chloride ion penetrability based on charge passed (AASHTO 2002)

Charge Passed (Coulomb)	Chloride Ion Penetrability
> 4,000	High
2,000 - 4,000	Moderate
1,000 - 2,000	Low
100 - 1,000	Very Low
< 100	Negligible

Evaluation of Chloride Ion Penetration by RCPT

The need for a rapid methodology to determine the chloride ions ingress into concrete was driven by the fact that using the classical diffusion cell requires considerable time for test completion. The use of the RCPT forces the chloride ions to move across the concrete specimen faster under the applied voltage gradient.

The RCPT has advocates and critics within the concrete technical community. In this report, both are addressed in terms of case studies.

The RCPT is a standard test and is a commonly used technique for rapid characterization of concrete in terms of penetrability of chloride ions (e.g., Saito & Ishimoiri 1995, Goodspeed et al., 1995, Thomas & Jones, 1996, Samaha & Hover, 1996). Joshi and Chan (2002) discussed the advantages and disadvantages of the RCPT. One of the main advantages mentioned is that RCPT is a quick test where it is completed in 6 hours. The RCPT was also found useful for quality control purposes. Other advantages of RCPT are: it has simple setup, results are easy to interpret, and results have good correlation with the results of 90-day ponding test. Russell (2001) described the RCPT as a rapid and easy test that can be used to test concrete specimens at any age.

Nevertheless, there are researchers who are critical of this test method (Stanish et al. 1997). The main criticism of the RCPT is that the conditions of measurement are severe and may cause physical and chemical changes to the specimen (Feldman et al. 1999). It is also pointed out that the current passing across the specimen is not only related to the chloride ions but to all ions in the pore water. During RCPT, the measurement is made before steady-state ion migration is reached. In addition, the high voltage applied across the concrete specimen leads to an increase in temperature, which will lead to increase in the charge passing across the specimen (Roy 1989, Geiker et al. 1990, Zhang & Gjorv 1991, Andrade 1993, Malek & Roy 1996). This effect is significant in concrete specimens of low quality, which would be characterized by RCPT as worse than they actually are. Russell (2001) mentioned that the RCPT could produce misleading results when carried out on concrete specimens containing calcium nitrite, steel reinforcement or carbon fibers.

Factors Affecting RCPT

The RCPT results are affected by many factors that can be categorized as follows:

1. Compositional factors: that are related to characteristics of the ingredients of the concrete such as the aggregate, water, cementitious materials, admixtures, etc.

2. Age factors: that are pertaining to the concrete age, concrete curing, etc.

The effects of the above-mentioned factors on the RCPT results are discussed in detail below.

The RCPT was used to investigate the effects of pozzolanas, silica fume, fly ash, and other supplementary materials on concrete resistance to chloride ions penetration (e.g., Ozyildirim & Halstead 1988, Plauto & Bilodeau 1988). There are different opinions on the use of the RCPT on concrete containing a combination of cementitious materials. Pfeiffer et al. (1994) criticized the use of the RCPT for concrete specimens with mineral admixtures and pozzolans since no adequate correlation with the ponding test has been validated. On the other hand, Hooton et al. (2000) and Ozyildirim (1993) concluded that correlations are valid between the RCPT results and the results of the ponding test for concrete with a variety of materials.

The effect of silica fume on the rapid chloride permeability test results was investigated by Ozyildirim (1994). Since the silica fume particles are almost one hundredth of the size of cement particles, their presence in concrete helps reduce pore sizes and also helps prevent long and continuous pore structures in concrete. RCPT results showed that the total charge passed through concrete with silica fume is less than one fourth of the charge passed through concrete without it. Comparison of the RCPT results and the 90-day ponding test results showed that both results are consistent provided that the mix ratio, curing, and age of concrete are identical. Ozyildirim (1998) conducted a study to investigate the effect of adding fly ash, silica fume, and slag in reducing the permeability of concrete. RCPT and the ponding test were conducted on concrete with plain Portland cement and on concrete containing fly ash, silica fume, and slag. Ozyildirim (1998) concluded that the RCPT is more convenient and relatively faster than the ponding test.

Ampadu et al. (1998) investigated the effects of adding slag to cement on the chloride resistance of concrete. Concrete specimens were prepared at water/binder ratios of 35% and 55% with slag replacement ratios of 30%, 50% and 70% in each water/binder category. Concrete specimens were subjected to the Accelerated Chloride Ion Diffusion (ACID) test, RCPT, electrical resistivity test, salt water absorption test, and mercury intrusion porosimetry test. Tests were performed at 7, 28 and 91 days of curing. Test results indicated that high slag replacement ratio and low water/binder ratio caused a reduction of the chloride ion diffusion coefficient through concrete. Based on the results of the various tests, Ampadu et al. (1998) found a correlation between the diffusion coefficient determined from ACID test and the total charge values of the RCPT. In addition, they observed that the chloride ion penetration depth measured with the salt ponding method (AASHTO T 259) correlated well with that measured from the RCPT.

Turgeon (2003) investigated the RCPT during the development of high performance concrete (HPC) pavement specifications for Mn/DOT. Concrete specimens were prepared with 35% ground granulated blast furnace slag (GGBFS) and were subjected to RCPT at 28 days. Results indicated that the 35% slag in the concrete mix significantly increased the concrete resistance to chloride penetration with a total passing charge of less than 2,100 Coulombs. Based on this research, Mn/DOT set the pilot specification limit at a maximum of 2,500 Coulombs at 28 days of curing for the HPC used in pavements. This level was assumed attainable with the use of 35% of GGBFS in the concrete mix.

Wee et al. (1999) investigated the influence of aggregate content of the concrete mix on the reliability of RCPT results. Test specimens were prepared from mixes with varying aggregate contents and were subjected to RCPT, soaking test, and electrical resistivity test. RCPT results showed that the plain cement mortar is relatively less resistant to chloride penetration compared to the plain cement concrete. The 90-day soaking test results indicated an opposite trend. The same results were also obtained when silica fume was added to the concrete and mortar mixes. Wee et al. (1999) concluded that the lower aggregate content of plain cement mortar misled the results of the RCPT. These results demonstrated the need to consider the volume fraction of the aggregate in the mix with and without silica fume when interpreting the results of RCPT.

Chia and Zhang (2002) investigated the water permeability and chloride penetrability of high-strength lightweight aggregate concrete in comparison to high-strength normal weight concrete with and without silica fume. For the concrete without silica fume, RCPT results showed that both lightweight and normal weight concrete had "high" chloride penetrability according to AASHTO T 277 description. On the other hand, the lightweight aggregate concrete with silica fume passed an average total charge of 316 Coulombs, which indicates that it has "very low"

chloride penetrability compared to an average total charge of 421 Coulombs passed through the normal weight concrete with silica fume. The RCPT results were found to be consistent with the results of the immersion and salt ponding tests conducted on both concrete types. Chia and Zhang (2002) indicated the existence of a direct relationship between the rapid chloride penetrability determined by AASHTO T-277 and the observed chloride penetration depth determined by the immersion and salt ponding tests.

A study was conducted by Feldman et al. (1994) to evaluate the effects of the experimental conditions and specimens on the test results. Factors such as temperature, AC impedance, initial DC current, charge passed, and chloride ion profiles during the application of current for RCPT were monitored. Results showed that while the 60 V DC is applied to older concrete specimens, resistivity may decrease and initial current and charge passed increase due to the increased concentration of chloride ions in the pore fluid. This may lead to overestimating the chloride penetrability. However, the results showed that simple measurement of the initial current or resistivity provided a ranking for four concrete specimens similar to the ranking obtained by the RCPT.

Zheng and Beaudoin (1999) investigated various aspects of the RCPT using the AC impedance technique. RCPT and measurement of impedance were conducted on various cement pastes of different ages. The cement pastes were prepared with and/or without silica fume and/or superplasticizer. Test results showed that the addition of silica fume significantly increased the impedance and reduced the total charge passed across the specimens, indicating an increase in resistance to chloride ions penetration.

Feldman et al. (1999) conducted another study to investigate the influence of concrete characteristics such as type of binder, mix proportions, and cure regime on the correlation between the total charge and both initial current and conductivity measured at the beginning of the RCPT. The study demonstrated the possibility of determining the relative quality of concrete specimens from the measurement of the initial current and conductivity at the beginning of the RCPT.

Aldia et al. (1999) investigated the effect of microcracking on durability of high-strength concrete. Specimens were prepared and then subjected to feedback-controlled splitting test to induce the microcracks. Chloride permeability of the cracked samples were evaluated by the RCPT. Test results indicated that only high strength concrete with low water/cement ratio was sensitive to the level of microcracking in terms of chloride permeability. Still, for microcracks up to 400 microns, high strength concrete with low water/cement ratio can be termed as concrete with "very low" chloride permeability according to AASTHO T 277 description.

Lim et al. (2000) investigated the relation between microcracking induced by uniaxial compression tests and concrete resistance to chloride penetration determined by the RCPT. The study found that a stress level known as the critical stress influenced the chloride permeability of concrete. When concrete specimens were stressed beyond the critical stress level to induce microcracks, the specimens were found to have high level of chloride permeability. When the critical stress level was not exceeded, the increase in permeability of the concrete samples was not significant.

Effect of Time

An extensive study was conducted by Hooton et al. (2001) to identify or develop a method, which could predict the penetration of chloride ions in concrete in relatively short time (less than 35 days). Different concrete mixes were prepared and subjected to various long and short-term standard test methods. In the first phase of this study (Phase-1), 8 different concrete mixes were used to prepare concrete specimens. The long-term standard tests used were: Resistance of Concrete to Chloride Ion Penetration (AASHTO T 259) and Accelerated Chloride Penetration into Hardened Concrete (NTBuild 443). Similarly, concrete samples from these mixes were also subjected to short-term testing procedures including the AASHTO T 277, and CTH Test or Rapid Migration Test (NTBuild 492). Mix design specifications of all 8 mixes are presented in Table 2.3.

Table 2.3: Phase-1 mix design specifications (after Hooton et al. (2001)).

Mix No. →	1	2	3	4	5	6	7	8
w/cm Ratio	0.50	0.45	0.45	0.45	0.45	0.35	0.35	0.25
Cement (kg/m^3)	335	362.5	333.5	290	235.6	418	384.6	513.4
Silica Fume (%)	0	0	8	0	0	0	8	8
Fly Ash (%)	0	0	0	20	0	0	0	0
Slag (%)	0	0	0	0	35	0	0	0
Coarse Aggregate (kg/m^3)	1,025	1,025	1,025	1,025	1,025	1,025	1,025	1,025
Fine Aggregate (kg/m^3)	710	698	688	682	690	695	684	580
Air Entrainer (mL/100 kg)	30	30	30	30	30	30	30	30
Water Reducer (mL/100 kg)	0	49	250	250	250	300	300	350
Superplasticizer (mL/100 kg)	0	0	196	0	0	498	250	770
Slump (mm)	160	100	70	165	170	175	30	55
Air Content (%)	7.5	8.0	9.0	8.0	8.5	5.5	8.0	3.0
Plastic Density (kg/m^3)	2,362	2,348	2,275	2,268	2,254	2,394	2,377	2,522

The results of the RCPT results of concrete specimens at different ages are shown in Figure 2.3.
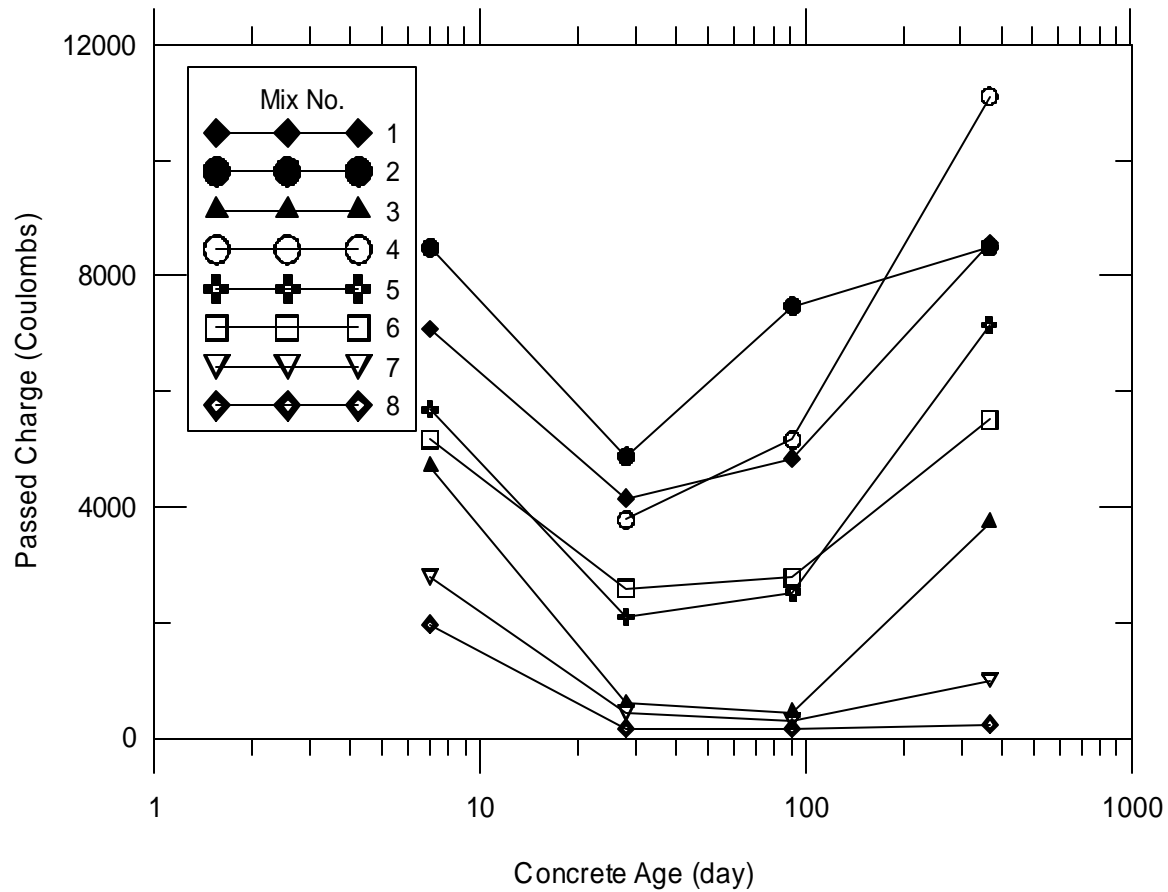
Figure 2.3: Phase-1 RCPT results at different ages of concrete.

In the second phase of the study (Phase-2), 25 different concrete mixes were made. Concrete specimens were subjected to AASHTO T 259, NTBuild 443, AASHTO T 277 and NTBuild 492 standard tests at different ages. Details of concrete mixes of interest to this study are presented in Table 2.4. The RCPT results for concrete specimens made out of these mixes at different ages are presented in Table 2.5.

In both phases (Phase-1 and Phase-2), whenever silica fume was used in the mixes, RCPT values decreased with time up to 91 days in Phase-1 and 118 days in Phase-2. But when tested at one year or later age, RCPT values increased from the lowest levels they reached at the first few months, as shown in Figure 2.3.

Table 2.4: Phase-2 mix design specifications (reproduced from Hooton et al. 2001).

Mix No. →	1	2	3	4	5	6	7	8	9
w/cm Ratio	0.50	0.45	0.45	0.35	0.35	0.35	0.45	0.25	0.35
Cement (kg/m^3)	335	290	319	367.8	238.3	301	181.3	513.4	384.6
Silica Fume (%)	0	0	0	0	8	8	0	8	8
Fly Ash (%)	0	20	0	0	0	20	0	0	0
Slag (%)	0	0	0	0	35	0	50	0	0
Metakaolin (%)	0	0	12	12	0	0	0	0	0
Coarse Aggregate (kg/m^3)	1,025	1,025	1,025	1,025	1,025	1,025	1,025	1,025	1,025
Fine Aggregate (kg/m^3)	710	682	686	682.5	668.5	660	680	580	684

Table 2.5: Phase-2 results of AASHTO T 277 (in Coulombs) of concrete specimens at different ages (Hooton et al. (2001)).

Mix No. →	1	2	3	4	5	6	7	8	9
28-day AASHTO T 277	6,217	2,799	336	257	179	287	976	176	388
118-day AASHTO T 277	2,939	726	290	190	147	131	614	154	338
393-day AASHTO T 277	2,528	426	294	205	140	169	293	-	481

The data presented in Tables 2.4 and 2.5 provided the following:
- Plain concrete (without any admixtures) is found to keep on becoming more resistant to chloride ingress with time (mix no. 1).
- Fly ash and slag both seem to play an important part in reducing chloride penetration from the very beginning and let concrete become more chloride resistant with time (mix no. 2 and 7).
- Metakaolin seems to be effective up to the first 4 months (based on 118-day test) of mixing, gradually increasing the chloride resistivity of concrete, but looses ground slightly after that period (verified by 393-day test) (mix no. 3 and 4).
- Silica fume works very effectively to block chloride penetration up to 4 months (verified by 118-day test). But after that period, it starts becoming gradually ineffective and by a year's period, its resistance to chloride decreases drastically (mix no. 8 and 9).
- Mixes incorporating a combination of pozzolans show mixed results (either decrease or increase in chloride resistivity) beyond 118-day tests depending upon the types of combinations. For example, mix no. 5 uses both silica fume and slag and its chloride resistivity seems to be marginally increased from 118-day to 393-day test. On the other hand, mix no. 6 uses silica fume and fly ash and its chloride resistivity seems to be decreased from 118-day to 393-day test.

Chapter 3
Aggregate Characteristics

This chapter presents the results of the laboratory testing program conducted to characterize the investigated aggregates. Mn/DOT project team identified sources of aggregates used in Mn/DOT highway construction projects. Mn/DOT personnel collected pre-determined quantities of coarse aggregate samples from 12 different sources and delivered them to UWM. Two types of fine aggregate were also collected and delivered to UWM.

The collected aggregates were subjected to a laboratory testing program to determine their physical properties including particle size distribution, specific gravity and absorption. In addition, powder samples from each aggregate type were prepared and used to measure the initial chloride content through the Rapid Chloride Test (RCT).

Aggregate Sources

The coarse aggregates collected for this study represent a wide range of types and sources used in Mn/DOT highway construction projects. A general description of each aggregate type is presented in Table 3.1. The aggregate types are of sedimentary, igneous, and metamorphic rock origin. The aggregate types include crushed limestone (calcium carbonates), crushed granite, gneiss, quartzite, and basalt. Figure 3.1 depicts pictures of the coarse aggregates selected for this study. The locations from which these aggregates were collected are shown in Figure 3.2.

Physical Properties

Laboratory tests were conducted on aggregate samples to evaluate their particle size distribution, specific gravity, and absorption. These tests were performed according to the applicable ASTM standard procedures.

Particle Size Distribution

This test was preformed to determine particle size distributions of the collected fine and coarse aggregate samples. The test was conducted in accordance with ASTM C 136: Sieve Analysis of Fine and Coarse Aggregates. Three samples of each aggregate type were tested to insure consistency of the test results. The particle size distribution curves of the fine aggregate (sand and grit) are shown in Figure 3.3. The particle size distribution curves for the coarse aggregates are depicted in Figure 3.4. Also shown in Figure 3.4 are the upper and lower aggregate size limits required by Mn/DOT concrete mix design specifications.

The particle size distribution curves of the coarse aggregate samples indicated that the gradation of these samples do not satisfy the Mn/DOT concrete mix design requirements. Therefore, all aggregate samples were processed using the required sieves and the proper fractions were combined to produce aggregates with identical gradations that were consistent with Mn/DOT specifications.

Table 3.1: General description of the aggregates used in this study

Aggregate Source	General Description and Predominant Constituents
Brielmaier	Crushed gneiss particles of angular shape and dark color
Michigan Limestone, Cedarville Plant	Crushed limestone particles of angular shape, rough surface and light color
Martin Marietta, St. Cloud	Crushed granite particles of angular shape and dark color
Ulland, Northwood, IA	Crushed dolomitic limestone particles of angular shape, rough surface and dark color
New Ulm	Crushed quartzite particles of angular shape and dark color
Barton	Mixture of basaltic, granitic, and limestone particles, mixture of smooth round particles and rough angular particles
Goldberg, Rochester	Crushed limestone particles of angular shape, rough surface and light color
Fischer, Apple Valley	Mixture of basaltic, granitic, and limestone particles, mixture of smooth round particles and rough angular particles
Kraemer, Burnsville	Crushed limestone particles of angular shape, rough surface and light color
Shiely (Larson), Grey Cloud	Crushed limestone particles of angular shape, rough surface and light color
Mark, Underwood	Mixture of basaltic, granitic, and limestone particles, mixture of smooth round particles and rough angular particles
Lanthier, Duluth	Mixture of basaltic, granitic, and limestone particles, mixture of smooth round particles and rough angular particles
Cemstone (Grit)	Fine particles of igneous rock origin
Aggregate Industries (Sand)	Fine particles of igneous rock origin

Note: coarse and fine aggregates used in this study were selected and collected by Mn/DOT project research committee and then shipped to University of Wisconsin-Milwaukee.

(a) Kraemer   (b) Brielmaier

(c) Mark

(d) Michigan Limestone

(e) New Ulm

(f) Fischer

Figure 3.1: Pictures of the investigated aggregates used in this study.

(g) Lanthier

(h) Larson

(i) Martin Marietta

(j) Goldberg

(k) Barton

(l) Ulland

Figure 3.1 (cont.): Pictures of the investigated aggregates used in this study.

Rapid Chloride Permeability Test
- Sample Locations -

69004
high igneous gravel

56003, gravel

73006, granite

27005, gravel

82002, carbonate

19106, carbonate

82001, sand

65065, gneiss

19001, gravel

19109, grit

52003, quartzite

55037
carbonate

93018, carbonate
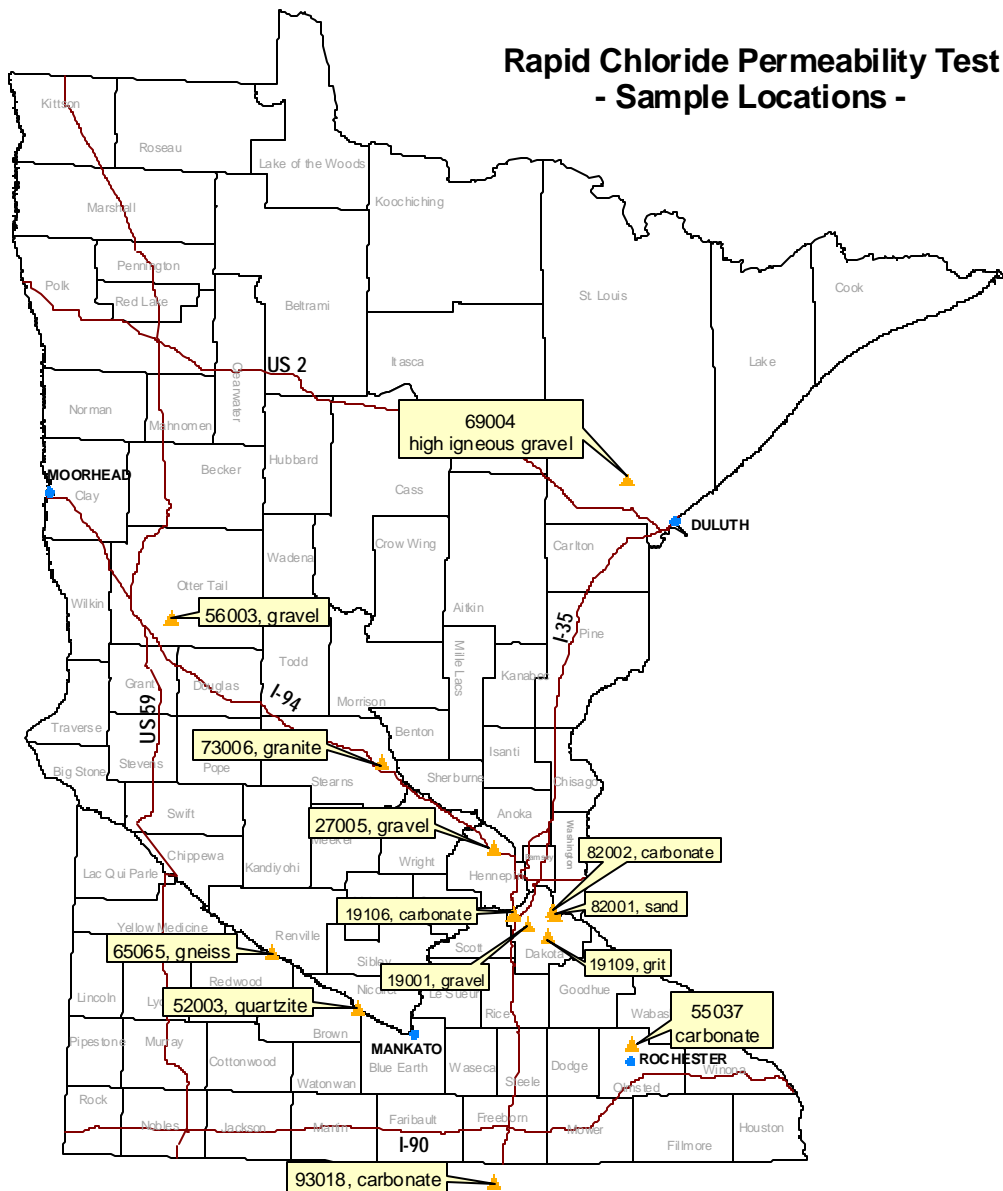
MN/DOT SOURCE #	NAME	MN/DOT SOURCE #	NAME
19001	Fischer, Apple Valley	65065	Brielmaier
19106	Kraemer, Burnsville	69004	Lanthier, Duluth
19109	Cemstone	73006	Martin-Marietta, St. Cloud
27005	Barton	82001	Aggregate Industries
52003	New Ulm	82002	Shiely (Larson), Grey Cloud
55037	Goldberg, Rochester	93018	Ulland, Northwood, IA
56003	Mark, Underwood	97001	Michigan Limestone, Cedarville Plant

Mn/DOT
Geology
8/20/03

Figure 3.2: Locations of the aggregates used in this study

17
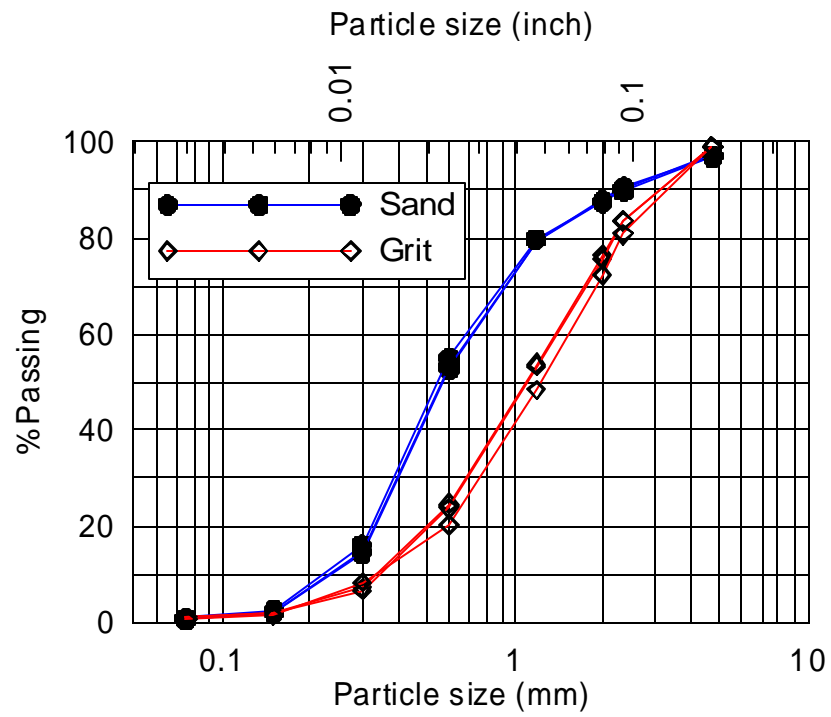
Figure 3.3: Particle size distribution curves of the fine aggregate used in this study.
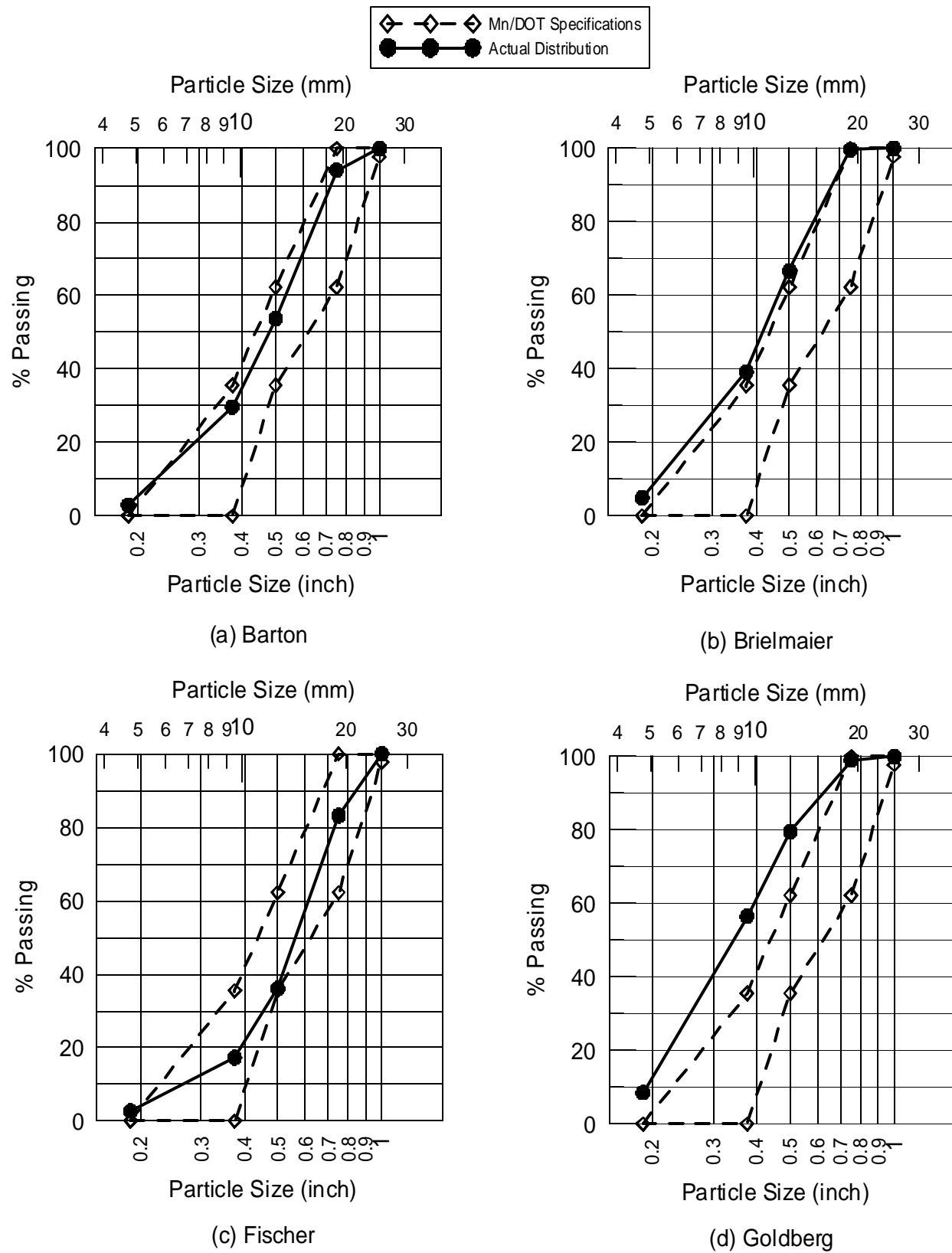
Figure 3.4: Particle size distribution curves of the coarse aggregates used in this study.
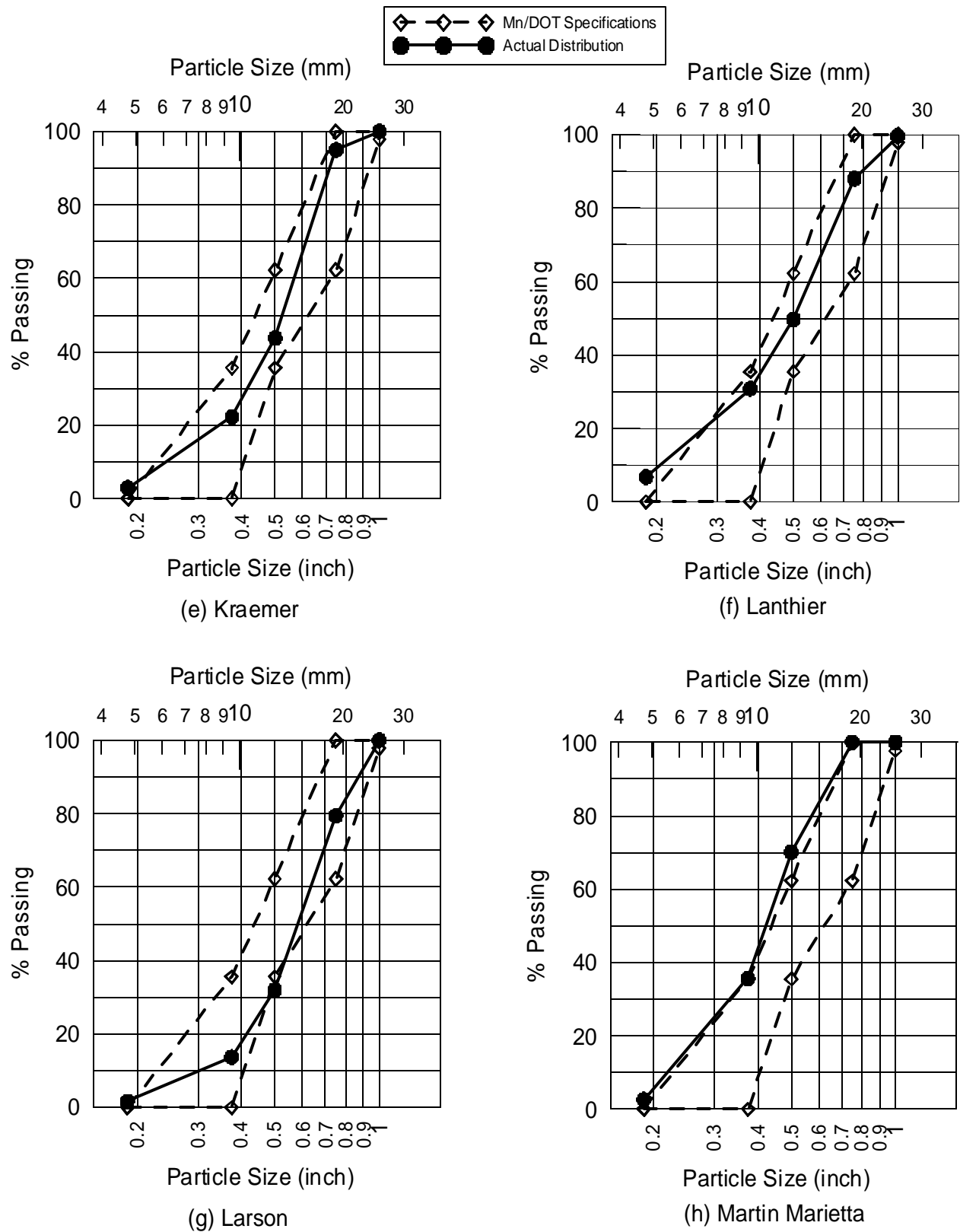
Figure 3.4 (cont.): Particle size distribution curves of the coarse aggregates used in this study.
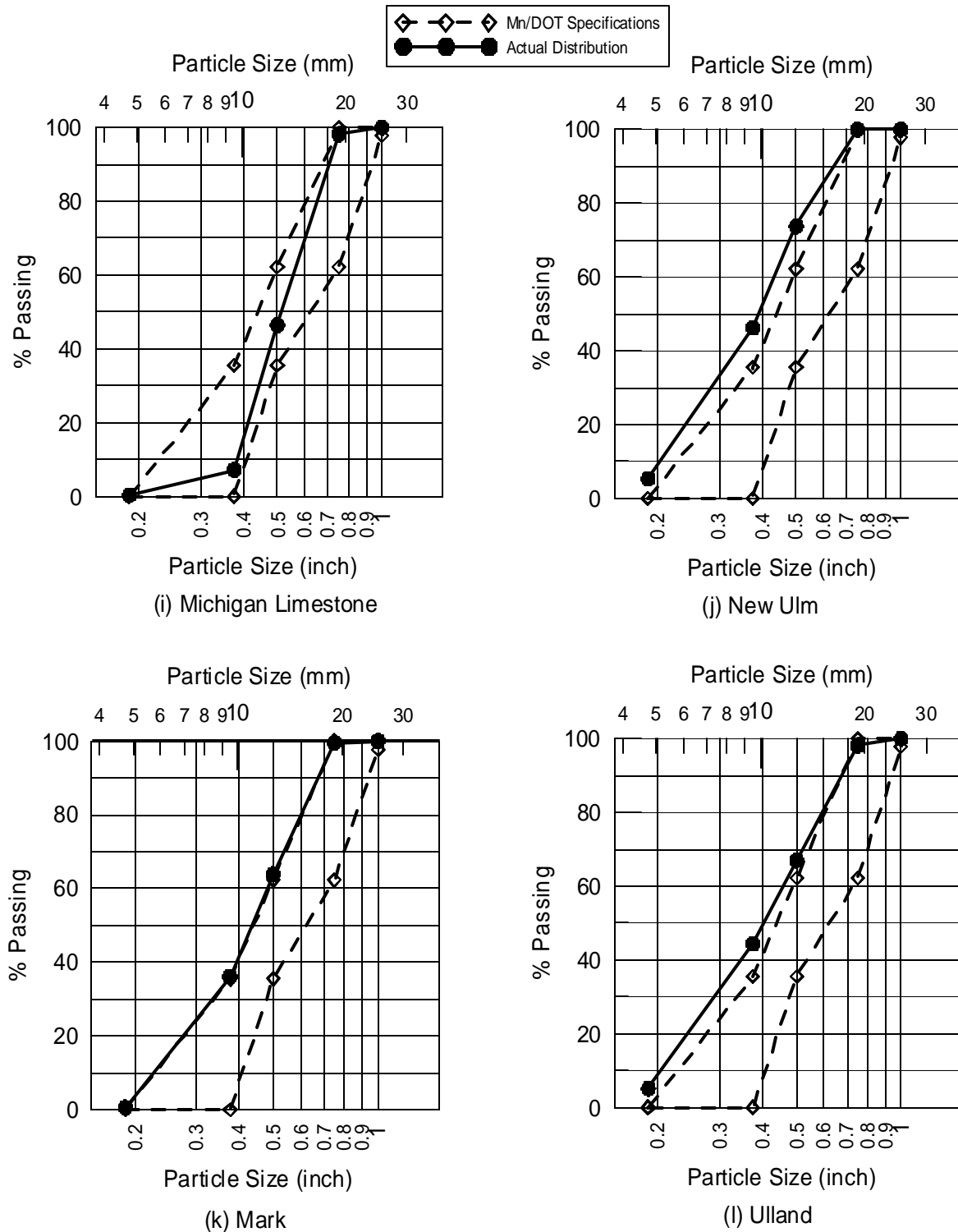
Figure 3.4 (cont.): Particle size distribution curves of the coarse aggregates used in this study

Specific Gravity and Absorption Tests

The aggregate samples were subjected to standard testing procedures to determine their bulk specific gravity, saturated surface dry (SSD) bulk specific gravity, and the apparent specific gravity. In addition, the absorption values of aggregates were determined. Specific gravity and absorption of aggregate samples were determined using ASTM C 127: Standard Test Method for Specific Gravity and Absorption of Coarse Aggregates.

Table 3.2 presents the results of the specific gravity and absorption tests of the coarse aggregates. Specific gravity values of the investigated coarse aggregates range from 2.62 to 2.76. The coarse aggregate from New Ulm possessed the lowest specific gravity with bulk specific gravity of 2.62. The highest bulk specific gravity was obtained for Michigan Limestone with a value of 2.76. The SSD bulk specific gravity values were higher than bulk specific gravity values and the apparent specific gravity values were the highest of all, as expected.

Absorption of the aggregate samples varied from 0.3% for Brielmaier gneiss to 2.2% for the limestone from Larson pit.

Table 3.2: Specific gravity and absorption calculation of different aggregate samples

Aggregate Type	Bulk Specific Gravity	Bulk Specific Gravity (SSD)	Apparent Specific Gravity	Absorption (%)
Shiely, Grey Cloud (Larson Pit)	2.64	2.69	2.80	2.20
Lanthier, Duluth	2.73	2.75	2.80	0.90
Ulland, Northwood, IA	2.70	2.72	2.78	1.10
St. Cloud (Martin-Marietta)	2.71	2.72	2.75	0.50
Goldberg, Rochester	2.66	2.70	2.78	1.70
Barton	2.66	2.70	2.75	1.20
Kraemer, Burnsville	2.63	2.69	2.79	2.10
Brielmaier	2.69	2.70	2.71	0.30
Fischer, Apply Valley	2.68	2.71	2.76	1.10
Mark, Underwood	2.66	2.69	2.74	1.10
New Ulm	2.62	2.63	2.66	0.70
Michigan Limestone	2.76	2.78	2.81	0.60

Chloride Content

The Rapid Chloride Test is designed for quick measurement of chloride content of fine particles including concrete powder drilled from hardened concrete in the field. RCT was developed by Germann Instruments in 1987. The need for this type of rapid chloride measurement test was realized because other existing methods such as potentiometric titration require measuring the chloride content by titration, which would involve a great deal of effort and significant amount of time. The amount of acid and water-soluble chlorides was measured as percent of total concrete mass. Figure 3.5 depicts picture of the RCT kit.

Correlation Between RCT and Other Standard Test Methods

Since the development of RCT method 15 years ago, studies were conducted to establish correlations between RCT and other standard laboratory potentiometric titration tests such as AASHTO T 260, ASTM C114 and other European standards. Studies showed that variations in results between RCT and other potentiometric titration tests were negligible. The correlations between these various test methods are shown in Figure 3.6.

A study was conducted by Germann Instruments (2003) on three different types of cement with known chloride contents to determine the accuracy of the RCT. The cement types were subjected to RCT and AASHTO T 260 separately. Test results from both tests were consistent with the actual amount of chlorides in these cement types. The test result is summarized in Table 3.3.

RCT on the Investigated Aggregate

The Rapid Chloride Test was conducted on the investigated coarse and fine aggregates to determine the ambient chloride level of each aggregate type. The test was performed on powder samples obtained by crushing the coarse and fine aggregates according to the test procedure described by the manufacturer of RCT equipment.
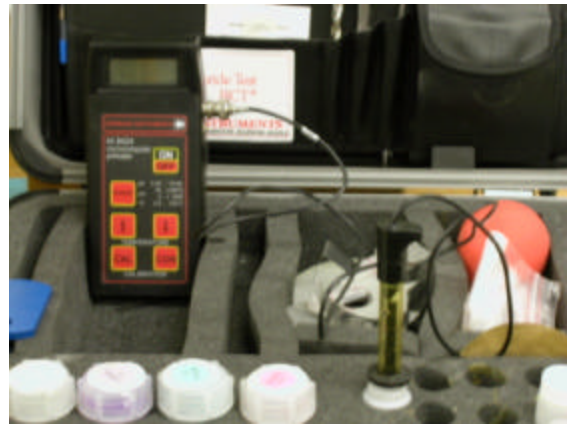
Figure 3.5: Rapid chloride test setup
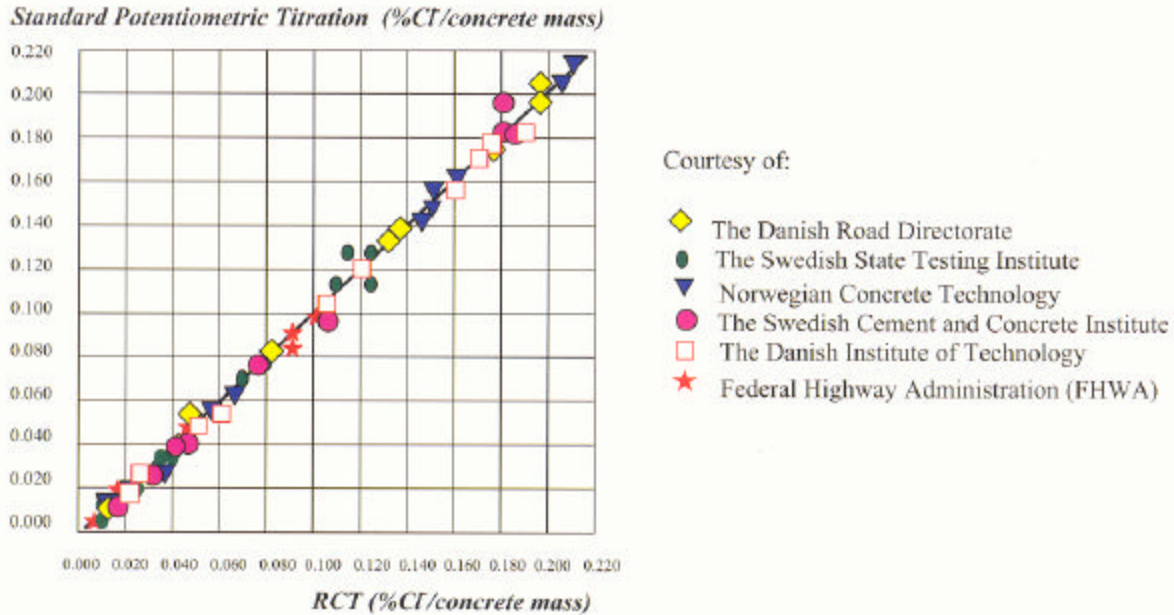
Figure 3.6: Comparison of chloride content determined by the standard potentiometric titration and RCT (Germann Instruments 2000).

Table 3.3: Comparison of test results by AASHTO T 260 and RCT on known chloride amounts (German Instruments 2003)

Cement Type	Known Chloride Amount (% Cl/mass)	AASHTO T 260 (% Cl/mass)	RCT (12-Hr) (% Cl/mass)
Portland Cement (CEM I)	0.023	0.024	0.022
	0.071	0.070	0.072
	0.328	0.314	0.321
Flyash Cement (CEM II/B-V)	0.020	0.019	0.019
	0.057	0.052	0.061
	0.244	0.229	0.238
Slag Cement (CEM III/B)	0.020	0.019	0.019
	0.056	0.052	0.059
	0.244	0.231	0.238

A large quantity of each aggregate was spread over a flat surface to select a representative sample for RCT. The selected sample weighed about 50 g. The aggregate sample was placed in a steel mortar and then crushed into powder by hammering with the pestle. After the sample was considered sufficiently fine, it was carefully placed into a plastic zipper-bag and stored in a safe and dry place. The mortar and pestle were cleaned by distilled water and dried before another aggregate type was powdered. Ample care was taken during this procedure to prevent the cross contamination of samples.

RCT Procedure

The acid soluble chloride content test was conducted on 14 aggregate samples: two powdered samples of sand and grit, and 12 powdered samples of coarse aggregates. Fresh calibration of the electrode was performed before conducting the RCT on the aggregate samples. The calibration was carried out first by removing the black cap at the tip of the electrode. Then, the Electrode Wetting Agent (EWA) was poured into the electrode to thoroughly wet the black cone at the tip. This liquid was allowed to seep through the tip and the tip was cleaned with distilled water, bloated dry and refilled with the same liquid again. The electrode was connected to the electrometer and the electrometer was turned on to make sure it was working.

Four vials of calibration liquids were provided with the test kit, each containing liquid of known chloride content. The prepared electrode was dipped into the first calibration liquid, then the electrometer reading was let to stabilize by waiting few minutes, and finally the reading was noted. The electrode was taken out of the liquid, bloated, cleaned with distilled water and again bloated. This procedure was followed for the remaining three calibration liquids and the readings were noted. These readings formed a basis for the evaluation of aggregate samples.

The RCT was carried out by carefully pouring 1.5 g of the aggregate powder into a clean and dry ampoule. The powder was compressed, using a steel cone, up to the red marking on the ampoule. Then the aggregate powder was poured into a vial containing 10 ml of chloride extraction liquid. The vial was tightly secured with a lid and continuously shaken for 5 minutes. The shaking was interrupted by occasionally letting out the gas formed in the vial. The electrode was dipped into the prepared sample solution and the electrometer reading was noted after the reading stabilized. Every time the tip of the electrode was bloated, cleaned with distilled water and bloated dry again to avoid cross-contamination. This procedure was repeated for all samples to be tested for that day. In addition to the 5 minutes test, a second reading was taken after one day.

RCT Results

The electrometer readings for four calibration liquids with known chloride content were plotted in a logarithmic graph. A best fitting straight line was passed through these four points. The chloride contents for each of the samples were found from the graph corresponding to their electrometer readings. A sample calibration curve is shown in Figure 3.7. The test results are summarized in Table 3.4.

Among all samples tested, only one was found with chloride content much higher compared to the others. Out of 12 samples that had less than 0.05% chloride contents, six had less than 0.01% and the rest had chloride contents between 0.01% and 0.05%. All percentages were per weight of the powder.

According to the test standard, the chloride content extracted by 24-hour test should be roughly 5% to 20% more than the chloride content extracted by 5-minute test (Germann Instruments 2000). Moreover, the sample solution left overnight should be able to extract 100% of chlorides from the sample, in which case chloride content might be even higher than 5% - 20% of 5-minute test. But most of the aggregate samples showed much larger differences in chloride

contents between 5-minute and 1-day tests. In fact, some of our samples had more than 100% increases in chloride contents from 5-minute tests to 1-day tests. Such a high increase in chloride contents from 5-minute tests to 1-day tests might have been due to larger sample particle sizes. Approximately 0.05 mm has been set as the appropriate particle size for doing this test (Petersen 1991). Finer particle sizes make it easy for chloride extraction liquid to remove chlorides faster from the particles and vice versa. In this context, 1-day results of RCT should be regarded more accurate. The 5-minute RCT test in this case might not have been able to extract as much of chlorides as it would for appropriate particle sizes.
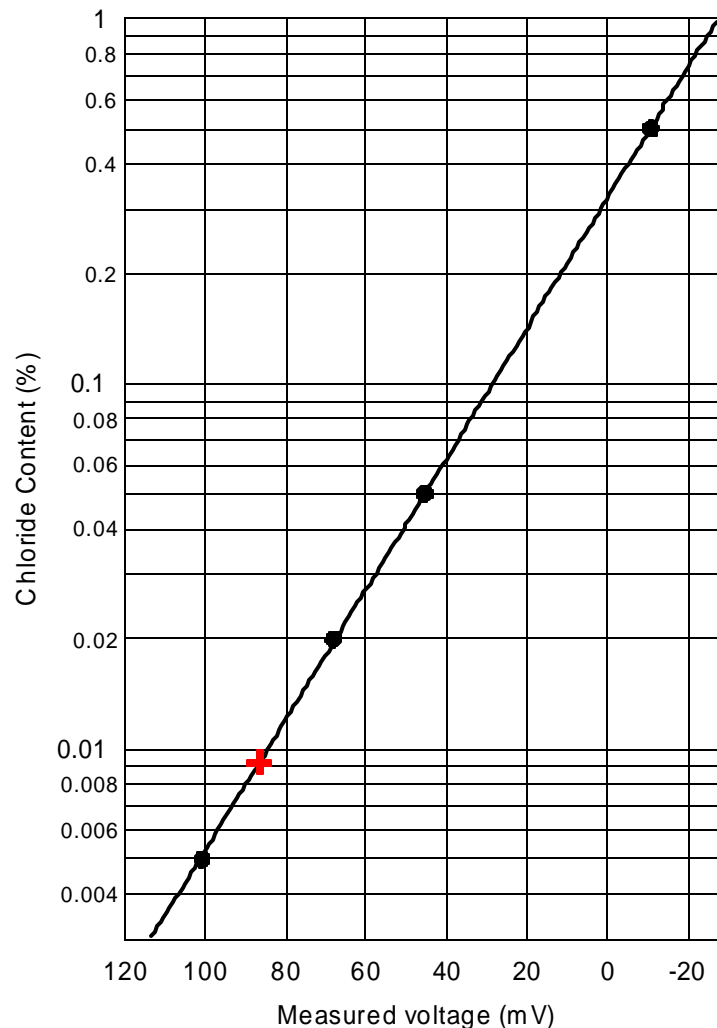
Figure 3.7: Calibration chart for 5-min RCT on a powdered aggregate sample

Table 3.4: Acid-soluble chloride contents for 5-minute and 1-day RCT tests for powdered aggregate samples

	5-Min Chloride %	1-Day Chloride %

Aggregate Type	(By wt. of Agg.)	(By wt. of Agg.)
Sachs Pit, Empire (Grit)	0.0059	0.0129
Shiely, Grey Cloud (Sand)	0.0057	0.0122
Mark, Underwood	0.0098	0.0202
Michigan Limestone, Cedarville Plant	0.1047	0.1236
Shiely (Larson), Grey Cloud	0.0441	0.0501
Kraemer, Burnsville	0.0366	0.0444
Lanthier, Duluth	0.0022	0.0044
Goldberg, Rochester	0.0224	0.0293
Ulland, Northwood, IA	0.0098	0.0098
Brielmaier	0.0030	0.0035
Fischer, Apply Valley	0.0061	0.0098
Martin Marietta, St. Cloud	0.0024	0.0029
Barton	0.0092	0.0226
New Ulm	0.0038	0.0058

Chapter 4
Concrete Mixing and Specimen Preparation

This chapter describes the laboratory program conducted to prepare fresh concrete according to Mn/DOT specifications. Each coarse aggregate type was used to prepare fresh concrete through three different batches. This is done to insure repeatability of test results and to obtain statistically valid results. The fresh concrete was subjected to slump and air content tests before it was accepted for placement in concrete cylinders. The concrete cylinders were cast and kept in a moist curing room until they were subjected to the laboratory-testing program.

Preparation of Concrete Ingredients

Quantities of the different ingredients needed to prepare a concrete mix following the Mn/DOT mixing specifications were calculated and presented in Table 4.1. Calculations were based on 1 cubic foot batches, which were sufficient to cast six 4-in cylinders, perform the slump test, and measure the air content of the fresh concrete. Quantities presented in Table 4.1 are based on the concrete mix specifications of Mn/DOT (designation 3Y43MS).

In order to meet Mn/DOT specifications, each coarse aggregate type was subjected to sieve analysis to separate the different aggregate fractions for subsequent remixing. This was performed due to the fact that sieve analysis of the as-received coarse aggregate samples did not satisfy the gradation requirements of Mn/DOT. Figure 4.1 depicts pictures of aggregate types separated on individual sieves.

Cementitious materials were obtained from sources approved by Mn/DOT. These include Portland cement Type I from Lafarge at Alpena, MI (LAFALMI), Class C flyash from Pleasant Prairie at Kenosha, WI (PLPKEWI), and densified microsilica fume from W.R. Grace & Co. at Cambridge, MA. The cementitious materials were obtained and stored in a dry place at room temperature. The quantities required for each concrete mix were weighed on accurate scale then stored in a clean dry container ready for use in concrete mixing.

Sand and grit (provided by Mn/DOT) were stored in a dry place at room temperature. The water content of these materials ranged from 0.1% to 0.2% and was considered negligible. These materials were regarded as dry and the required quantities of water were added to have them at saturated surface dry condition.

The coarse aggregate fraction of each size was soaked in water for a period of 24 hours. Then, the water was drained and the aggregate particle surface was dried using clean towels until a saturated surface dry condition was reached. The required aggregate quantities were weighed immediately, then placed in a single container, and covered with a moist towel to prevent drying of the absorbed water.

Normal tap water was used in concrete mixing. The water was poured into a container, which was left to maintain room temperature. The required water quantity was weighed just before mixing to prevent evaporation.

Table 4.1: Quantities of all ingredients used to prepare 1 ft³ of Portland cement concrete according to Mn/DOT specifications

Aggregate Types	Specific Gravity (SSD) of Coarse Aggregate	Weight of 1" - 3/4" Aggregate (lb)	Weight of 3/4" - 1/2" Aggregate (lb)	Weight of 1/2" - 3/8" Aggregate (lb)	Weight of 3/8" - #4 Aggregate (lb)	Weight of Dry Sand (lb)	Weight of Dry Grit (lb)	Water Absorbed by Sand and Grit (lb)	Total Wt. of Water (lb)
Larson	2.69	1.08	17.34	13.00	17.34	23.40	35.28	0.93	10.39
Lanthier	2.75	1.09	17.50	13.13	17.50	23.62	35.61	0.94	10.40
Ulland	2.72	1.09	17.42	13.07	17.42	23.51	35.44	0.93	10.40
Martin Marietta	2.72	1.09	17.42	13.06	17.42	23.50	35.43	0.93	10.40
Goldberg	2.70	1.09	17.36	13.02	17.36	23.43	35.32	0.93	10.39
Barton	2.70	1.08	17.34	13.01	17.34	23.41	35.29	0.93	10.39
Kraemer	2.69	1.08	17.32	12.99	17.32	23.38	35.24	0.93	10.39
Brielmaier	2.70	1.08	17.35	13.01	17.35	23.41	35.29	0.93	10.39
Fischer	2.71	1.09	17.39	13.04	17.39	23.46	35.37	0.93	10.40
Mark	2.69	1.08	17.32	12.99	17.32	23.38	35.25	0.93	10.39
New Ulm	2.63	1.07	17.16	12.87	17.16	23.16	34.92	0.92	10.38
MI Limestone	2.78	1.10	17.58	13.18	17.58	23.72	35.76	0.94	10.41

Material Types	Weight (lb)	Volume (ml)
Cement	18.07	N/A
Fly Ash	4.81	N/A
Microsilica	1.22	N/A
Water	9.46	N/A
Air-entrainer	-	40
Plastisizer	-	36

(a) Larson Aggregate

(b) Mark aggregate

Figure 4.1: Pictures of aggregate types separated on individual sieves to comply with Mn/DOT gradation specifications

The Mn/DOT approved air-entrainer admixture AXIM and the midrange water-reducing admixture EUCON MR were obtained and used in this research. The admixtures were acquired and stored in a container at room temperature. The required quantities were measured using graduated cylinder. However, during the different trial mixes, these quantities were adjusted so that the slump and air content values fall within the range required by Mn/DOT specifications.

Since these admixtures are in a liquid form, adjustment was made to the total quantity of water used.

Concrete Mixing

A 5 ft^3 power-driven mixer was used for concrete mixing as shown in Figure 4.2. The mixer bucket was first rinsed with water to moisten the inside wall and prevent the loss of mixing water. On the side, the air-entrainer was added to the mixing water and then thoroughly mixed. The measured quantity of coarse aggregate was placed inside the mixer bucket followed by approximately one-fourth of the mixing water. The mixer was turned on and allowed to run for a few rounds. Then the sand and grit were added while the mixer was running followed by cement, fly ash, and microsilica. The plasticizer was added to the mix while mixer was running. At this time, the count was started for the 3 minutes mixing time followed by 3 minutes of rest and a final 2 minutes of additional mixing. Figure 4.3 depicts pictures of the various stages of concrete mixing process. The concrete was then dumped into a pan for slump, air-content, and unit weight measurements. The cylinders were then cast if the slump and air-content results fell within the specification limits of Mn/DOT.

Figure 4.2: The 5-ft^3 concrete mixer used to prepare fresh concrete

(a) Preparing SSD coarse aggregate

(b) Weighing coarse aggregate
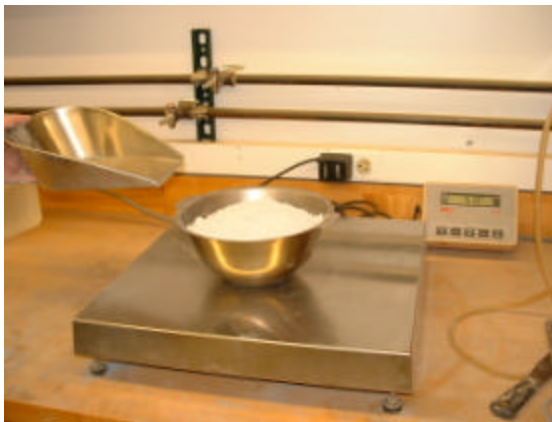
(c) Weighing flyash

(d) Weighing cement

(e) Placing ingredients in mixer
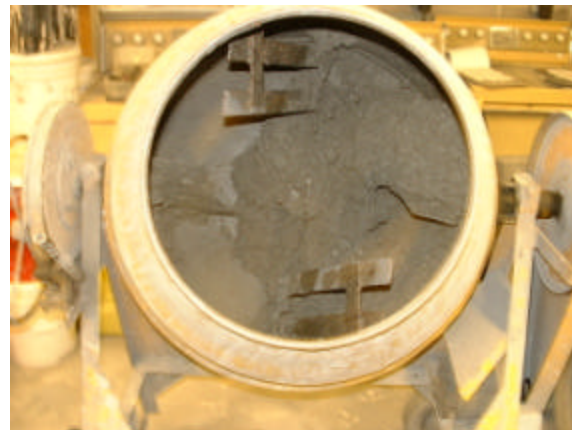
(f) Mixing concrete

Figure 4.3: Concrete ingredients preparation and mixing

Concrete trial mixes were started using aggregate from Brielmaier. The first two mixes failed to satisfy the specifications of Mn/DOT and therefore were discarded. In the first trial mix, a 5-gallon mixer was used to produce a 0.65 ft^3 of concrete. The mixer was not able to rotate the

bucket even though it was a new one. The research team continued the mix by hand for the sake of testing the procedure. No hand mixing operation was used during the course of the research project. Another trial mix using Michigan limestone failed to satisfy the Mn/DOT specification. There was not enough ½″ fraction of Michigan aggregate to perform three trial mixes. Therefore, only two successful trial mixes were done using Michigan limestone. Table 4.2 presents the results of concrete mixing using the investigated aggregates. The table also shows if the 1″ aggregate size was used or not, the date of mixing, and the number of cylinders cast.

Testing of Fresh Concrete

Slump Test

The slump of the fresh concrete was measured following ASTM C 143: Standard Test Method for Slump of Hydraulic-Cement Concrete. The slump cone and tamping rod were moistened before performing the test. Slump test results are presented in Table 4.3. Examination of Table 4.3 indicates that all concrete trial mixes possessed slump values less than 5″ as required by Mn/DOT research project committee. The lowest slump value of 1.8″ was measured for trial mix # 4 using Brielmaier aggregates, while the maximum slump value of 4.6″ was obtained from trial mix #3 using Mark aggregate.

Air Content Test

Measurement of the air content of the fresh concrete was performed in accordance with ASTM C 231: Standard Test Method for Air Content of Freshly Mixed Concrete by Pressure Method. The air content apparatus used is equipped with a Type-B meter as shown in Figure 4.4a. Figure 4.4 depicts pictures of the various stages of measuring the unit weight and air content of the fresh concrete mixes.

The results of air content measurement for all trial mixes are shown in Table 4.3. According to Mn/DOT specifications, the desirable value of air content was 6.5% with, a range of 5 to 8%. The air content of the successful trial mixes shown in Table 4.3 ranges between 5 and 8%, which is consistent with Mn/DOT requirements. Table 4.3 also presents the unit weight of the fresh concrete, which varies between 137.4 and 145.4 lb/ft^3.

Casting Concrete Cylinders

The results of testing on the fresh concrete were compared with the specification limits of Mn/DOT. If the test results were in compliance with Mn/DOT specifications, then 4″ cylinders were cast. Cylinders were prepared by placing the freshly mixed concrete into 4″ diameter by 8″ long plastic cylinders. The cylinders were placed on a plate type external vibrator for compaction. The concrete was placed in the cylinders in three layers while the vibrator was turned on. Once the desirable compaction was achieved, the top of each cylinder was leveled.

Table 4.2: Results of different trials of concrete mixing

Aggregate Source	Trial Mix Number	Date of Mixing	Results	Comments
Brielmaier	1	10/08/03	Failed	Small mixer did not work. Had to hand-mix. Out of MnDOT specification limits. 1" – ¾" agg. used. 5 cylinders cast.
	2	10/09/03	Failed	Exceeded MnDOT specification limits. 1" – ¾" agg. used. No cylinders cast.
	3	10/10/03	Passed	Within MnDOT specification limits. 1" – ¾" agg. not used. 7 cylinders cast.
	4	10/13/03	Passed	Within MnDOT specification limits. 1" – ¾" agg. not used. 6 cylinders cast.
	5	10/14/03	Passed	Within MnDOT specification limits. 1" – ¾" agg. not used. 6 cylinders cast.
Michigan Limestone	1	10/15/03	Passed	Within MnDOT specification limits. 1" – ¾" agg. used. 6 cylinders cast.
	2	10/17/03	Failed	Exceeded MnDOT specification limits. 1" – ¾" agg. used. No cylinders cast.
	3	10/18/03	Passed	Within MnDOT specification limits. 1" – ¾" agg. used. 6 cylinders cast.
Martin Marietta	1	10/21/03	Passed	Within MnDOT specification limits. 1" – ¾" agg. used. 6 cylinders cast.
	2	10/23/03	Passed	Within MnDOT specification limits. 1" – ¾" agg. not used. 6 cylinders cast.
	3	10/24/03	Passed	Within MnDOT specification limits. 1" – ¾" agg. not used. 6 cylinders cast.
Ulland	1	10/28/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	2	10/30/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 5 cylinders cast.
	3	10/31/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
New Ulm	1	11/04/03	Passed	Within MnDOT specification limits. 1" – ¾" agg not used. 6 cylinders cast.
	2	11/06/03	Passed	Within MnDOT specification limits. 1" – ¾" agg not used. 6 cylinders cast.
	3	11/13/03	Passed	Within MnDOT specification limits. 1" – ¾" agg not used. 6 cylinders cast.
Barton	1	11/14/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	2	11/17/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	3	11/17/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.

Table 4.2 (cont.): Results of different trials of concrete mixing

Aggregate Source	Trial Mix Number	Date of Mixing	Results	Comments
Goldberg	1	11/18/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	2	11/19/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	3	11/19/03	Passed	Within MnDOT specification limits. 1" – ¾" agg not used. 6 cylinders cast.
Fischer	1	11/20/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	2	11/21/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	3	11/21/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 5 cylinders cast.
Kraemer	1	11/26/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	2	11/26/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	3	11/26/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
Larson	1	12/01/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	2	12/01/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	3	12/01/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
Mark	1	12/03/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	2	12/03/03	Passed	Within MnDOT specification limits. 1" – ¾" agg not used. 6 cylinders cast.
	3	12/03/03	Passed	Within MnDOT specification limits. 1" – ¾" agg not used. 6 cylinders cast.
Lanthier	1	12/05/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	2	12/05/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.
	3	12/05/03	Passed	Within MnDOT specification limits. 1" – ¾" agg used. 6 cylinders cast.

Table 4.3: Test results on fresh concrete trial mixes

Aggregate Source	Trial Mix Number	Date of Mixing	Slump (in)	Air Content (%)	Unit wt of Fresh Concrete g_{conc} (pcf)
Brillmeir	3	10/10/03	3.6	8.0	137.4
	4	10/13/03	1.8	6.8	140.4
	5	10/14/03	3.3	7.5	143.2
Michigan Limestone	1	10/15/03	3.9	7.4	141.7
	3	10/18/03	2.8	6.2	143.7
Martin Marietta	1	10/21/03	2.8	6.4	142.4
	2	10/23/03	3.0	6.6	142.0
	3	10/24/03	2.8	6.0	142.7
Ulland	1	10/28/03	3.2	6.8	141.8
	2	10/30/03	2.5	6.1	142.6
	3	10/31/03	3.5	7.0	141.3
New Ulm	1	11/04/03	2.8	6.4	140.8
	2	11/06/03	2.8	6.0	141.5
	3	11/13/03	3.1	6.8	140.6
Barton	1	11/14/03	3.0	6.8	141.9
	2	11/17/03	3.4	7.0	142.0
	3	11/17/03	4.3	7.8	140.8
Goldberg	1	11/18/03	2.9	6.2	143.3
	2	11/19/03	3.3	7.4	139.3
	3	11/19/03	3.5	7.3	140.6
Fischer	1	11/20/03	3.4	6.3	141.7
	2	11/21/03	3.1	6.8	141.1
	3	11/21/03	2.5	5.0	145.4
Kraemer	1	11/26/03	2.9	6.6	141.2
	2	11/26/03	3.3	6.3	142.6
	3	11/26/03	3.8	6.8	141.7
Larson	1	12/01/03	3.1	6.5	141.3
	2	12/01/03	3.1	6.8	142.0
	3	12/01/03	3.3	6.5	142.1
Mark	1	12/03/03	4.4	6.8	142.1
	2	12/03/03	3.8	6.8	141.8
	3	12/03/03	4.6	7.3	140.5
Lanthier	1	12/05/03	3.0	6.1	144.6
	2	12/05/03	3.7	6.7	143.2
	3	12/05/03	4.3	7.2	141.6

(a) Air content apparatus

(b) Compacting concrete in the bowl

(c) Leveling concrete surface

(d) Unit weight determination

(e) Bowl rolling

(f) Air content measurement

Figure 4.4: Measurement of unit weight and air content of fresh concrete.

Cylinders were removed from the top of the vibrator then covered with a plastic cap and kept in upright position in a safe place for 24 hours. Figure 4.5 shows pictures of casting 4″ concrete cylinders of the investigated mixes. Table 4.2 presents the number of cylinders cast from each trial mix.

Curing of Cylinders

The cylinders were removed from the plastic mold after 24 hours and placed in the moist curing room. Curing was maintained by continuous sprinkling of water vapor in the entire room and the room temperature was maintained at about 23° C. The curing was provided uninterruptedly until testing. Figure 4.6 shows pictures of concrete cylinders being removed from the molds and placed in the moist curing room.

Compressive Strength Test

Compressive strength tests on concrete cylinders were conducted according to ASTM C 39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Concrete cylinders of 28 days of age were compressed to failure using the compression-testing machine as shown in Figure 4.7. The failure load was recorded and used to calculate the compressive strength of the concrete cylinders. The failure mode of each cylinder was also observed and recorded. Results of the compressive strength test of the concrete cylinders are presented in Table 4.4.

Examination of Table 4.4 shows that the compressive strength of concrete cylinders exceeded the minimum of 4,300 psi required by Mn/DOT except for two cylinders. Trial mix #5 of Brielmaier aggregate and trial mix # 1 of Kraemer aggregates possessed a compressive strength of 3,684 and 3,923 psi respectively. Other trial mixes of these aggregates showed a compressive strength that exceeded Mn/DOT requirements. The maximum compressive strength of a cylinder was obtained from trial mix #3 for a cylinder cast with Fischer aggregate.

(a) Pouring concrete from mixer into the pan

(b) Placing concrete in 4-inch cylinders

(c) Leveling surfaces of concrete cylinders

(d) Completing vibratory compaction

(e) Placing cylinders in a safe place

(f) Covering cylinder with plastic caps

Figure 4.5: Various steps in casting 4-inch concrete cylinders

(a) Removing concrete cylinder from molds

(b) Concrete cylinders labeled at the top

(c) Concrete cylinders labeled at the side

(d) Concrete cylinders stored in curing room

(e) Concrete cylinders stored in curing room

(f) Concrete cylinders stored in curing room

Figure 4.6: Picture of concrete cylinder stored in the curing room.

(a) Compression test machine

(b) Concrete cylinder being tested

(c) Data acquisition system

(d) Tested concrete cylinders

Figure 4.7: Compressive strength test of concrete cylinders.

Table 4.4: Compressive strength of 4″ concrete cylinders

Aggregate Source	Trial Mix Number	Date of Mixing	Compressive Strength at 28 Days (psi)	Failure Mode
Brielmaier	3	10/10/03	4,433	Columnar
	4	10/13/03	5,109	Cone
	5	10/14/03	3,684	Cone
Michigan Limestone	1	10/15/03	5,451	Cone
	3	10/18/03	5,252	Columnar
Martin Marietta	1	10/21/03	5,650	Cone
	2	10/23/03	5,833	Cone
	3	10/24/03	6,183	Cone
Ulland	1	10/28/03	6,207	Cone
	2	10/30/03	6,764	Cone
	3	10/31/03	5,387	Cone
New Ulm	1	11/04/03	4,735	Cone
	2	11/06/03	5,284	Cone
	3	11/13/03	5,929	Cone
Barton	1	11/14/03	5,507	Cone
	2	11/17/03	5,602	Cone
	3	11/17/03	5,539	Cone
Goldberg	1	11/18/03	6,549	Cone
	2	11/19/03	5,650	Cone
	3	11/19/03	5,666	Cone
Fischer	1	11/20/03	5,785	Cone
	2	11/21/03	5,435	Cone
	3	11/21/03	6,915	Columnar
Kraemer	1	11/26/03	3,923	Cone
	2	11/26/03	6,271	Cone
	3	11/26/03	6,366	Cone
Larson	1	12/01/03	6,135	Cone
	2	12/01/03	4,743	Columnar
	3	12/01/03	4,353	Cone
Mark	1	12/03/03	5,165	Cone
	2	12/03/03	5,228	Cone
	3	12/03/03	5,165	Cone
Lanthier	1	12/05/03	5,785	Cone
	2	12/05/03	5,149	Cone
	3	12/05/03	5,220	Cone

Chapter 5
RCPT Results and Analysis

This chapter presents the RCPT results on the concrete specimens at different ages. For each aggregate type, three concrete specimens were subjected to RCPT at 28, 56, and 91 days of age. Analysis of the test results is also presented in this chapter.

Rapid Chloride Permeability Test and Results

Concrete specimens were subjected to RCPT to evaluate the ability of the concrete made of different aggregate types for resisting chloride ions penetration. RCPT was performed on the specimens according to the AASHTO T 277 standard procedure.

Sample Preparation and Conditioning

The 4″ concrete cylinders were continuously kept inside the moist curing room until the time of testing. A concrete specimen 2″ (±0.125″) thick was cut from the top of each cylinder using a water-cooled diamond saw. Cylinders were cut for conditioning 1 day before the date of testing. For example, specimens were cut for conditioning at age of 27 days when RCPT was scheduled at age of 28 days. Table 5.1 presents a timetable for conditioning and testing concrete specimens. Appendix A presents the dimensions of all specimens cut for conditioning and subsequent RCPT testing.

The conditioning procedure was conducted by coating the circumference of the specimen with a rapid setting marine epoxy. After the epoxy dried, the specimen was placed in a vacuum desiccator where vacuum was applied and maintained for a period of 3 hours. Then, the desiccator was filled with de-aerated water while vacuum was maintained. The specimen was left in water under vacuum for one hour. Vacuum pressure was released and specimen was left in water for 18 hours. Figure 5.1 depicts picture of a concrete specimen under conditioning.

Specimen Testing

After 18 hours, the specimen was subjected to RCPT according to the timetable shown in Table 5.1. The concrete specimen was mounted inside the RCPT cell as shown in Figure 5.2. Each cell is equipped with rubber gaskets, which does not require specimen-cell sealant. Specimen was mounted so that NaCl reservoir faces the top face of the specimen. The cell reservoirs were filled one with 3% NaCl solution and 0.3 N NaOH solution. The cell was then connected to the data acquisition system and personal computer. A temperature probe was also connected to the cell to measure the changes in the temperature during testing. Figure 5.3 depicts pictures of concrete specimens under RCPT. The test was conducted according to the AASTHO T 277 standard procedure in which specimen ends were subjected to a voltage difference of 60 V for a period of 6 hours. The test setup is fully automated and controlled by software. The RCPT software acquires, with time, the charge passed, the temperature, and the current during testing time as shown in Figure 5.4.
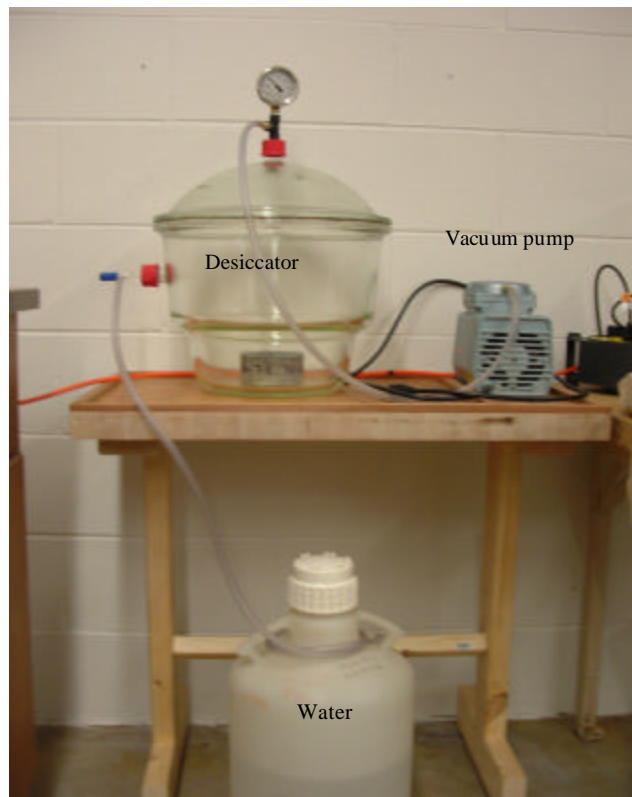
Figure 5.1: Conditioning of concrete specimen

Table 5.1: Timetable for conditioning and testing of concrete specimens

| Aggregate Source | Trial Mix Number | Date of Mixing | Rapid Chloride Permeability Testing Dates | | | | | |
| | | | 28-Days | | 56-Days | | 91-Days | |
			Conditioning	Test	Conditioning	Test	Conditioning	Test
Brielmaier	3	10/10/2003	11/6/2003	11/7/2003	12/4/2003	12/5/2003	1/8/2004	1/9/2004
	4	10/13/2003	11/9/2003	11/10/2003	12/7/2003	12/8/2003	1/11/2004	1/12/2004
	5	10/14/2003	11/10/2003	11/11/2003	12/8/2003	12/9/2003	1/12/2004	1/13/2004
Michigan Limestone	1	10/15/2003	11/11/2003	11/12/2003	12/9/2003	12/10/2003	1/13/2004	1/14/2004
	3	10/18/2003	11/14/2003	11/15/2003	12/12/2003	12/13/2003	1/16/2004	1/17/2004
Martin Marietta	1	10/21/2003	11/17/2003	11/18/2003	12/15/2003	12/16/2003	1/19/2004	1/20/2004
	2	10/23/2003	11/19/2003	11/20/2003	12/17/2003	12/18/2003	1/21/2004	1/22/2004
	3	10/24/2003	11/20/2003	11/21/2003	12/18/2003	12/19/2003	1/22/2004	1/23/2004
Ulland	1	10/28/2003	11/24/2003	11/25/2003	12/22/2003	12/23/2003	1/26/2004	1/27/2004
	2	10/30/2003	11/26/2003	11/27/2003	12/24/2003	12/25/2003	1/28/2004	1/29/2004
	3	10/31/2003	11/27/2003	11/28/2003	12/25/2003	12/26/2003	1/29/2004	1/30/2004
New Ulm	1	11/4/2003	12/1/2003	12/2/2003	12/29/2003	12/30/2003	2/2/2004	2/3/2004
	2	11/6/2003	12/3/2003	12/4/2003	12/31/2003	1/1/2004	2/4/2004	2/5/2004
	3	11/13/2003	12/10/2003	12/11/2003	1/7/2004	1/8/2004	2/11/2004	2/12/2004
Barton	1	11/14/2003	12/11/2003	12/12/2003	1/8/2004	1/9/2004	2/12/2004	2/13/2004
	2	11/17/2003	12/14/2003	12/15/2003	1/11/2004	1/12/2004	2/15/2004	2/16/2004
	3	11/17/2003	12/14/2003	12/15/2003	1/11/2004	1/12/2004	2/15/2004	2/16/2004
Goldberg	1	11/18/2003	12/15/2003	12/16/2003	1/12/2004	1/13/2004	2/16/2004	2/17/2004
	2	11/19/2003	12/16/2003	12/17/2003	1/13/2004	1/14/2004	2/17/2004	2/18/2004
	3	11/19/2003	12/16/2003	12/17/2003	1/13/2004	1/14/2004	2/17/2004	2/18/2004
Fischer	1	11/20/2003	12/17/2003	12/18/2003	1/14/2004	1/15/2004	2/18/2004	2/19/2004
	2	11/21/2003	12/18/2003	12/19/2003	1/15/2004	1/16/2004	2/19/2004	2/20/2004
	3	11/21/2003	12/18/2003	12/19/2003	1/15/2004	1/16/2004	2/19/2004	2/20/2004
Kraemer	1	11/26/2003	12/23/2003	12/24/2003	1/20/2004	1/21/2004	2/24/2004	2/25/2004
	2	11/26/2003	12/23/2003	12/24/2003	1/20/2004	1/21/2004	2/24/2004	2/25/2004
	3	11/26/2003	12/23/2003	12/24/2003	1/20/2004	1/21/2004	2/24/2004	2/25/2004
Larson	1	12/1/2003	12/28/2003	12/29/2003	1/25/2004	1/26/2004	2/29/2004	3/1/2004
	2	12/1/2003	12/28/2003	12/29/2003	1/25/2004	1/26/2004	2/29/2004	3/1/2004
	3	12/1/2003	12/28/2003	12/29/2003	1/25/2004	1/26/2004	2/29/2004	3/1/2004
Mark	1	12/3/2003	12/30/2003	12/31/2003	1/27/2004	1/28/2004	3/2/2004	3/3/2004
	2	12/3/2003	12/30/2003	12/31/2003	1/27/2004	1/28/2004	3/2/2004	3/3/2004
	3	12/3/2003	12/30/2003	12/31/2003	1/27/2004	1/28/2004	3/2/2004	3/3/2004
Lanthier	1	12/5/2003	1/1/2004	1/2/2004	1/29/2004	1/30/2004	3/4/2004	3/5/2004
	2	12/5/2003	1/1/2004	1/2/2004	1/29/2004	1/30/2004	3/4/2004	3/5/2004
	3	12/5/2003	1/1/2004	1/2/2004	1/29/2004	1/30/2004	3/4/2004	3/5/2004

(a) RCPT cell

(b) Rubber gasket around specimen
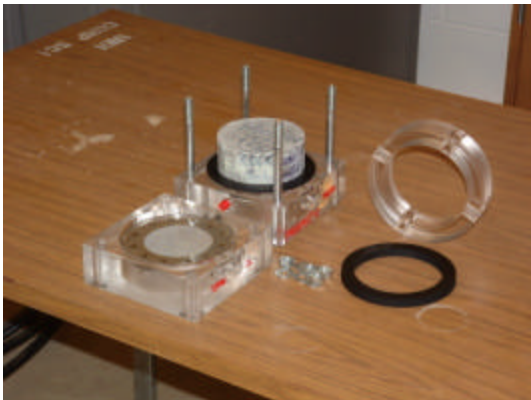
(c) Specimen place in the cell

(d) Rubber gasket at the top of specimen

Figure 5.2: Mounting the concrete specimen into the RCPT cell

(a) NaCl and NaOH solutions

(b) Filling cell reservoirs

(c) Connecting cell to data acquisition system
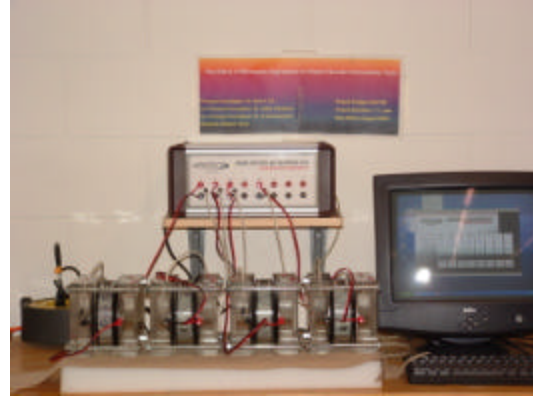
(d) Running the RCPT software

(e) Running RCPT on 4 concrete specimens

(f) Concrete specimens under RCPT

Figure 5.3: RCPT on concrete specimens
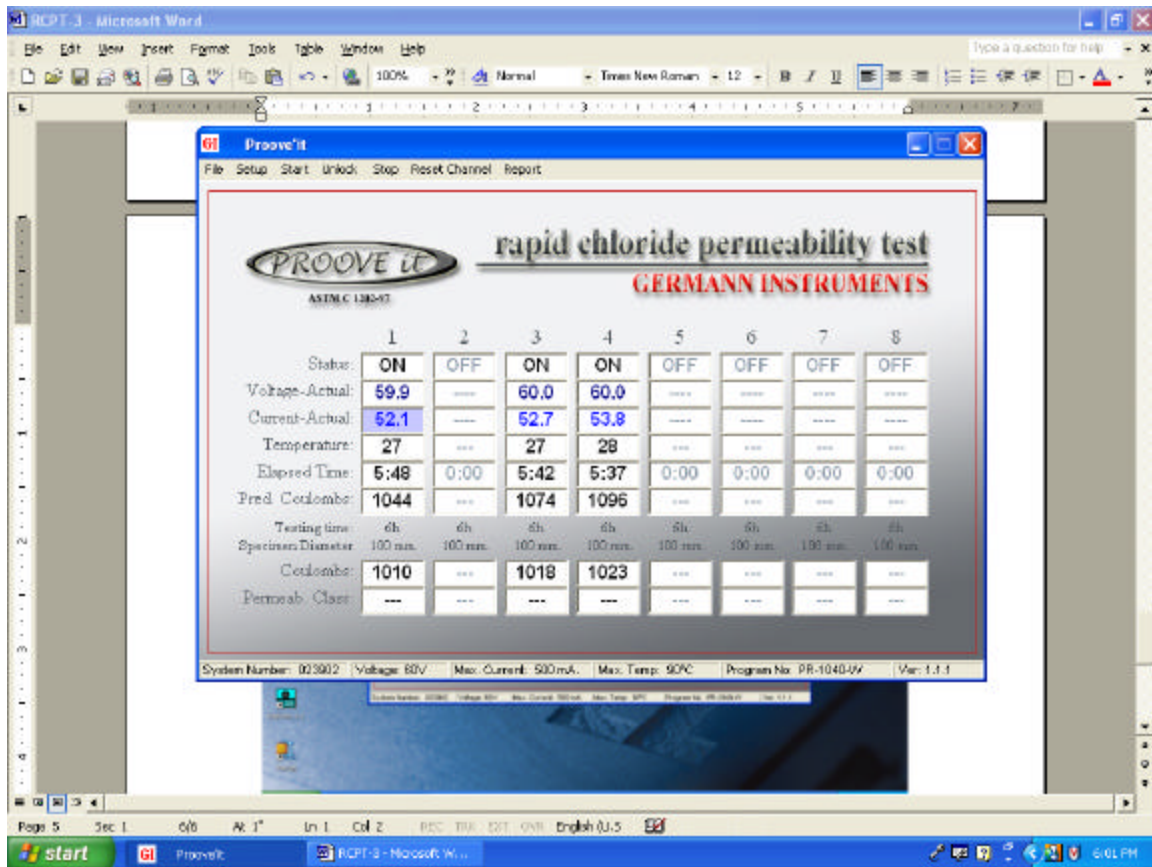
Figure 5.4: The RCPT software used to run the test and acquire the data.

Test Results

The RCPT was conducted on concrete specimens at ages of 28, 56, and 91 days. RCPT results are presented in Table 5.2. For 10 out of 105 specimens tested, the specimen age was different than the intended 28 and 56 days as shown in Table 5.2. This was due to the unavailability of the research team to perform the test at the required time.

Analysis of Test Results

Analysis of test results was conducted to investigate the effect of the aggregate type on the chloride ions penetration. Preparation of the concrete specimens was done under well-controlled conditions (e.g. separating coarse aggregate fractions, using same fine aggregates, using same cementitious materials, air content range, slump range, etc.). Therefore, the three specimens of each aggregate type were considered sufficient for performing basic statistical analysis on the test results.

Inspection of the test results presented in Table 5.2 shows that, for specimens at 28 days of age, the highest measured total charge of 2,713 Coulombs passed through the concrete specimen made of Kraemer crushed limestone, while the lowest total charge of 1,341 Coulombs passed through the specimen made of Brielmaier gneiss. Figure 5.5 shows bar charts of the total charge passed through the concrete specimens made of the investigated aggregate types at age of 28 days. For each aggregate type, the results of testing on three specimens are presented with the exception of Michigan limestone, where only two successful trial mixes were obtained out of 5 total trial mixes. No more trial mixes were done since all coarse aggregates available were consumed in the 5 trial mixes. The bar charts shown in Figure 5.5 indicate that the test results of the specimens from the three trial mixes of each aggregate type are within acceptable range of repeatability. In order to quantify the repeatability of test results, basic statistical analysis was conducted and presented in Table 5.3. For concrete specimens of 28 days of age, the coefficient of variation for the total charge passed through concrete specimens made of the same aggregate type varies between 3 and 15. The coefficient of variation indicates the variability of the test results of the concrete specimens made of the same aggregate type. This range of variability is considered tolerable and reflects repeatability of the test results. For concrete specimens of 28 days of age, the average charge passed specimens of the same aggregate type ranges from 1,452 to 2,606 Coulombs.

Results of RCPT on concrete specimens of 56 and 91 days of age are presented in Table 5.2. For concrete specimens of 56 days of age, the total charge passed through varies between 740 and 1,757 Coulombs with the highest for specimens cast with Larson limestone and the lowest for specimens made of New Ulm quartzite. The coefficient of variation in the test results within concrete specimens made of the same aggregate type ranges from 1 to 21. For concrete specimens of 91 days of age, the total charge passed ranges from 514 to 1,393 Coulombs with the highest for specimens cast with Larson limestone and the lowest for specimens made of New Ulm quartzite. The coefficient of variation in the test results within concrete specimens made of the same aggregate type ranges from 3 to 21.

50

Table 5.2: Results of RCPT conducted on concrete specimens at different ages

Sample Type	Trial Mix #	Sample Position	Total Charge Passed (Coulomb)		
			28-Day	56-Day	91-Day
Brielmaier	3	Top	1,550 [33]*	1,116	677
	4	Top	1,341 [30]*	872	691
	5	Top	1,465 [29]*	989	655
Michigan Limestone	1	Top	1,878	1,122	732
	3	Top	1,519	829	584
Martin Marietta	1	Top	1,589	912	644
	2	Top	1,769	933	647
	3	Top	1,559	984	588
Ulland	1	Top	2,096	1,175	974
	2	Top	1,941	1,174	827
	3	Top	2,004	1,113	814
New Ulm	1	Top	1,782	925	701
	2	Top	1,351	740	514
	3	Top	1,565	949	587
Barton	1	Top	1,918	944	662
	2	Top	2,151	1,044 [62]*	822
	3	Top	2,004	1,125 [62]*	802
Goldberg	1	Top	2,432	1,074 [61]*	984
	2	Top	2,065	1,104	899
	3	Top	2,140	1,096 [60]*	896
Fischer	1	Top	2,081	1,044 [58]*	959
	2	Top	1,925	1,032 [57]*	916
	3	Top	1,835	798 [57]*	637
Kraemer	1	Top	2,648	1,463	1,195
	2	Top	2,713	1,695	1,269
	3	Top	2,457	1,460	1,194
Larson	1	Top	2,598	1,668	1,206
	2	Top	2,332	1,163	1,110
	3	Top	2,666	1,757	1,393
Mark	1	Top	1,717	1,402	903
	2	Top	1,788	1,138	883
	3	Top	2,124	1,234	958
Lanthier	1	Top	1,549	867	661
	2	Top	1,533	809	749
	3	Top	1,451	904	686

* Indicates the age of specimen at the time of testing
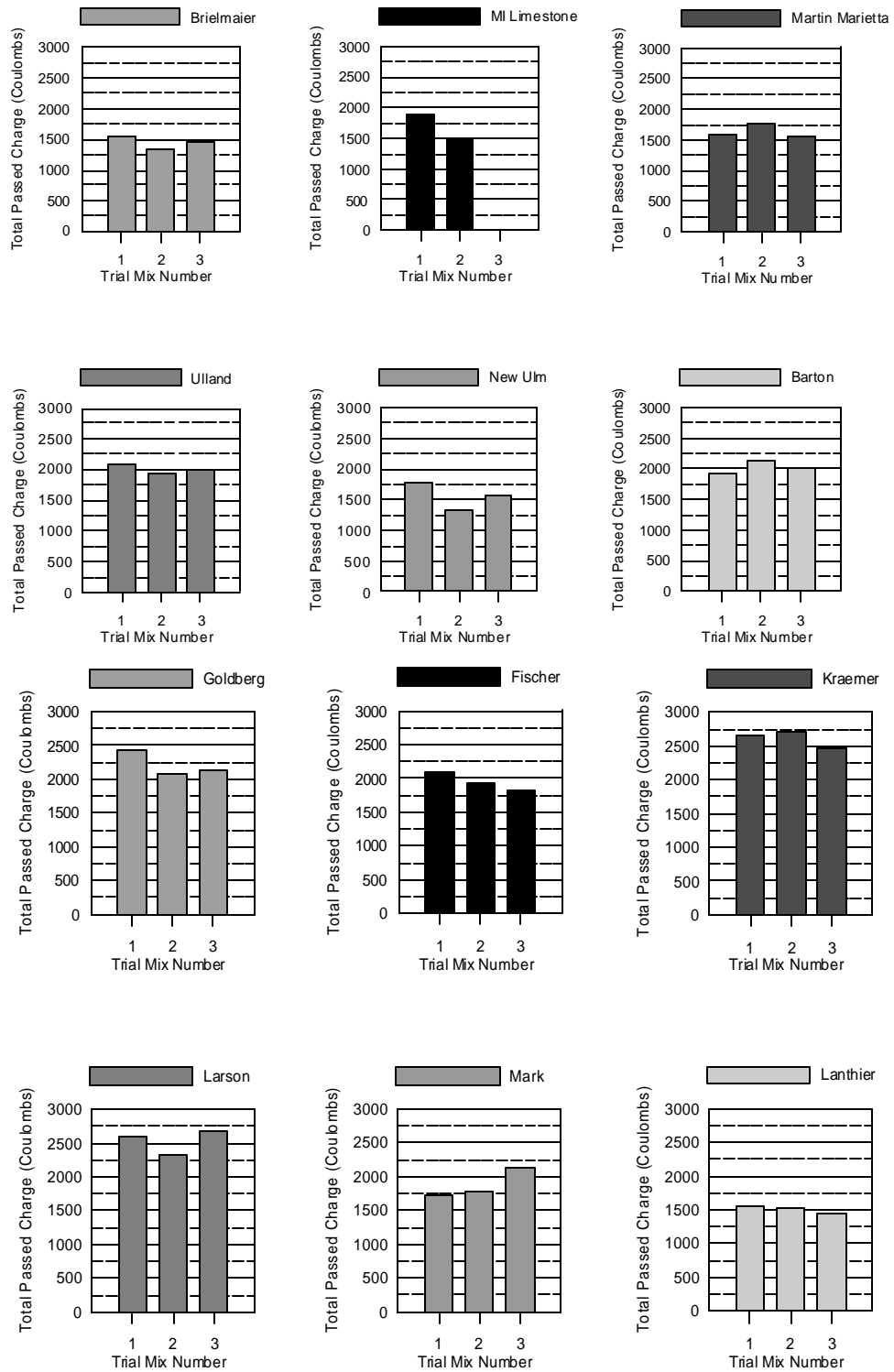
Figure 5.5: Bar chart of the total charge passed through specimens at age of 28 days

Table 5.3: Basic statistical analysis of the test results

| Sample Type | Total Charge Passed (Coulomb) | | | | | | | | |
| | 28-Day | | | 56-Day | | | 91-Day | | |
	m	s	COV (%)	m	s	COV (%)	m	s	COV (%)
Brielmaier	1,452	105	7	992	122	12	674	18	3
Michigan Limestone	1,699	254	15	976	207	21	658	105	16
Martin Marietta	1,639	114	7	943	37	4	626	33	5
Ulland	2,014	78	4	1,154	36	3	872	89	10
New Ulm	1,566	216	14	871	114	13	601	94	16
Barton	2,024	118	6	1,038	91	9	762	87	11
Goldberg	2,212	194	9	1,091	16	1	926	50	5
Fischer	1,947	124	6	958	139	14	837	175	21
Kraemer	2,606	133	5	1,539	135	9	1,219	43	4
Larson	2,532	177	7	1,529	320	21	1,236	144	12
Mark	1,876	217	12	1,258	134	11	915	39	4
Lanthier	1,511	53	3	860	48	6	699	45	6

Legend: μ = Mean, σ = Standard deviation, COV = Coefficient of variation

The test results at 28, 56, and 91 days of age are presented in Figures 5.6, 5.7, and 5.8. Test results (Tables 5.2 and 5.3 and Figures 5.6 and 5.7) indicate that the total charge passed across concrete specimens made of the same aggregate type decreases with an increase in concrete age. For example, Michigan limestone concrete specimens from trial mix #1 showed a decrease in the total charge passed from 1,878 Coulombs at age of 28 days to 732 Coulombs at age of 91 days. This is a reduction of about 61% of the initial total charge passed in approximately two months. The reason for this reduction is believed to be the continuous hydration of the cement, which results in re-crystallization of cementitous materials inside the pore space. This reaction results in reducing the pore space and pore connectivity inside the concrete and therefore the penetration of chloride ions.

The AASHTO T 277 description of concrete specimens based on the test results is shown in Table 2.2. The AASHTO description was used here to classify the concrete specimens made of each aggregate type based on the average total charge passed. The classification is presented in Table 5.4 for concrete specimens of 28, 56, and 91 days of age. For concrete specimens of 28 days of age, seven were described as concrete of "low" chloride ion penetrability and five as concrete of "moderate" chloride ion penetrability. This description was changed with specimen age in which after 91 days 10 specimens were described as concrete of "very low" chloride ion penetrability and two of "low" chloride ion penetrability.

The results of RCPT on specimens were grouped in Tables 5.5 to 5.7 based on the type of the coarse aggregate used to prepare concrete specimens. Table 5.5 presents the RCPT results of the concrete mixed with crushed limestone. The crushed limestone aggregate was more porous compared to the other types of aggregate used. This could be the reason behind the relative higher total passed charge through specimens made of crushed limestone. With the exception of Michigan limestone, the specimens made of crushed limestone showed "moderate" chloride ion penetrability at age of 28 days, which was decreased to "low" and "very low" chloride ion penetrability at 91 days.

Table 5.6 presents the RCPT results on specimens made with crushed metamorphic and igneous rocks. These concrete specimens showed "low" and "very low" chloride ion penetrability at 28 and 91 days of age, respectively. The aggregates obtained from the sites in Table 5.6 were hard, solid, and less pervious. This might be a major reason for the low total charge passed through the specimens made of these aggregate types. The RCPT results on specimens made with mixture of non-crushed (smooth round aggregate) and crushed aggregates of igneous, metamorphic, and sedimentary rock origin are presented in Table 5.7. This concrete showed "low"/"moderate" and "very low" chloride ion penetrability at 28 and 91 days of age, respectively.

Analysis was conducted to correlate the total charge passed to the compressive strength of concrete specimens and absorption of coarse aggregates. As shown in Figure 5.9, there is no correlation between the total charge passed and the compressive strength of concrete specimens. The data used only for specimens at 28 days of age. On the other hand, good correlation was achieved between the aggregate absorption and the total charge passed. Linear functions were obtained for specimens at 28, 56, and 91 days of age. Figure 5.10 depicts graphs of the relationship between coarse aggregate absorption and total charge passed.
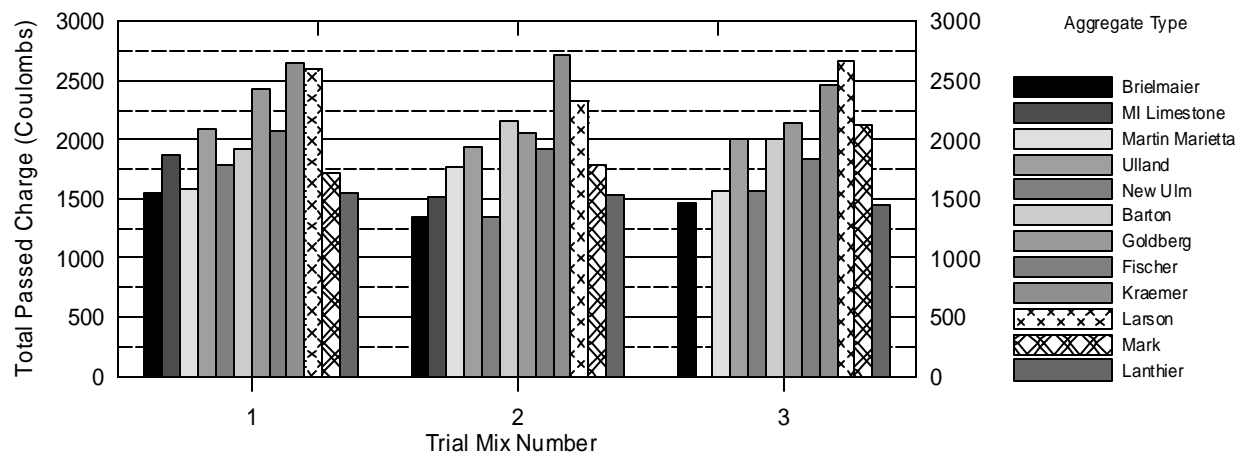
(a) Concrete specimens at 28 days of age
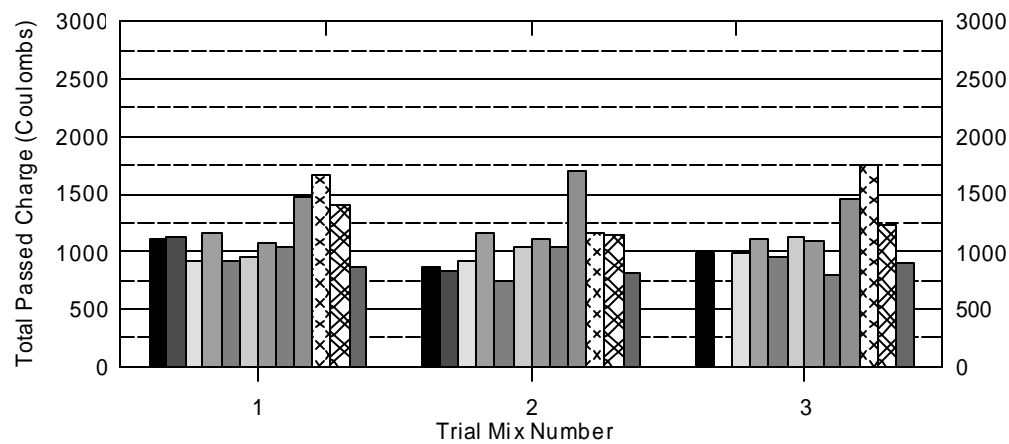
(b) Concrete specimens at 56 days of age
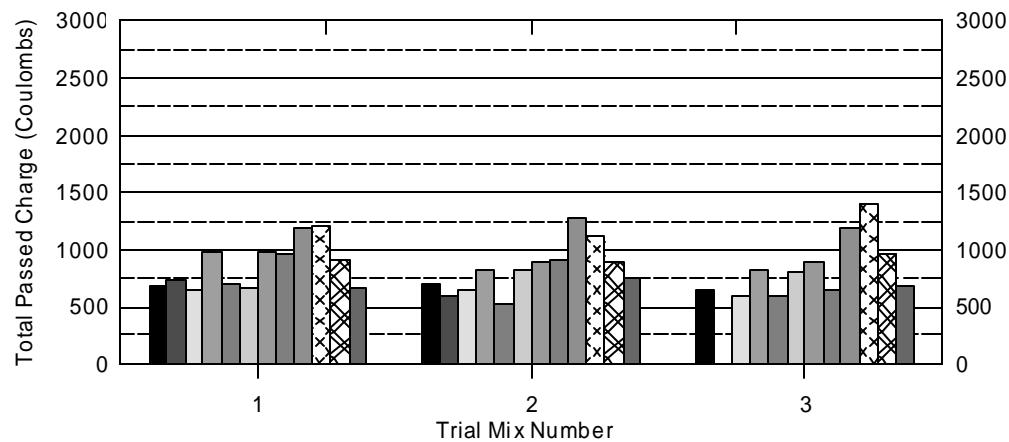
(c) Concrete specimens at 91 days of age

Figure 5.6: Bar chart of the total charge passed through specimens at different ages

Total Passed Charge (Coulombs)

Trial Mix Number

Aggregate Type

Brielmaier
MI Limestone
Martin Marietta
Ulland
New Ulm
Barton
Goldberg
Fischer
Kraemer
Larson
Mark
Lanthier
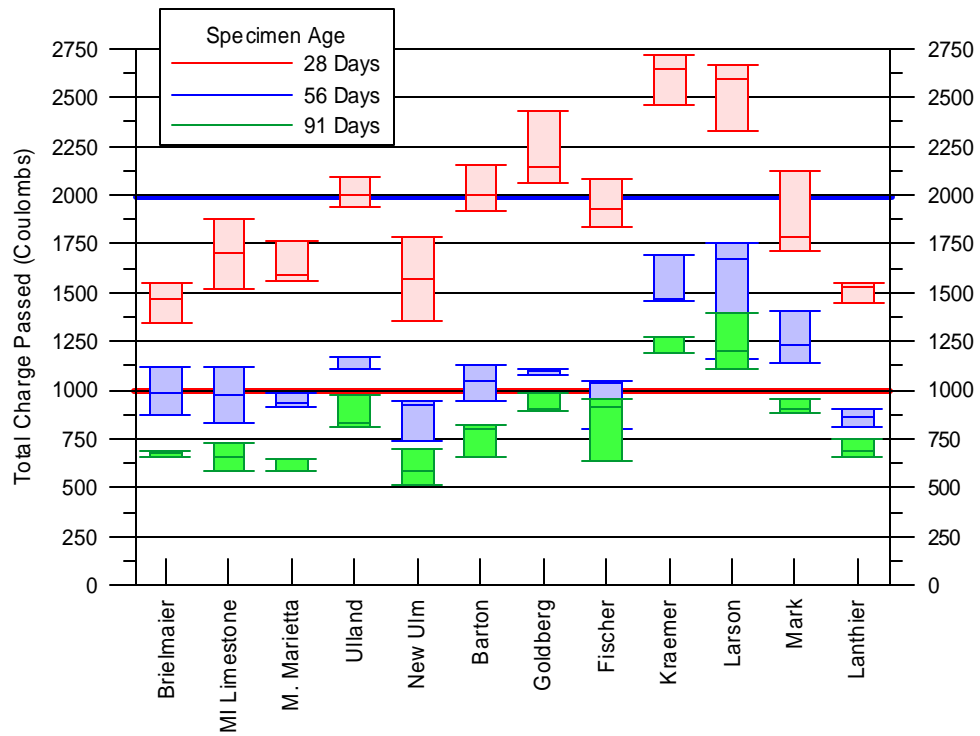
(a) Variation of total charge passed with time
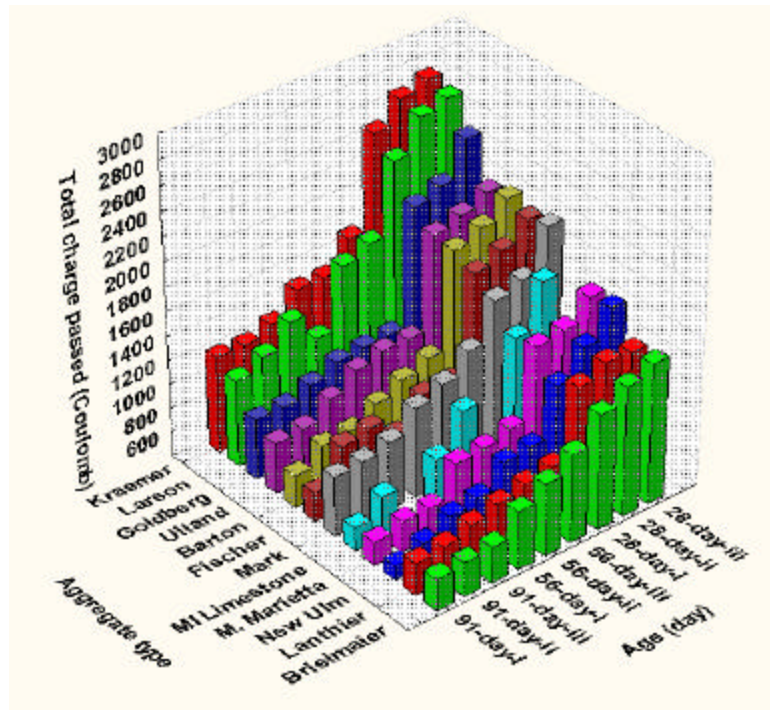
(b) 3-D bar chart of the test results

Figure 5.7: RCPT results at different ages
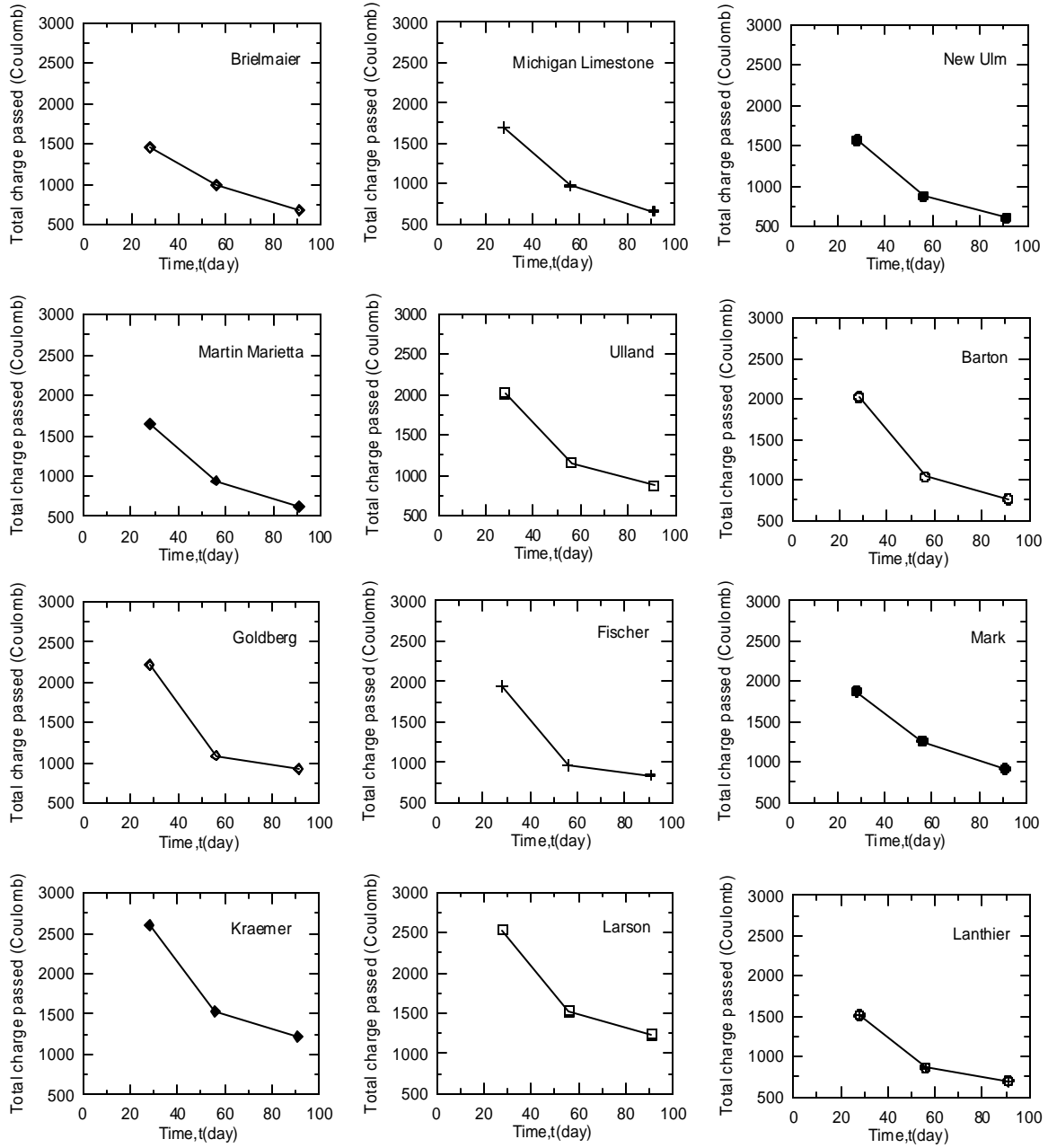
Figure 5.8: Variation of total charge passed with time (age of specimen)

Table 5.4: Interpretation of the RCPT results according to AASHTO T 277

| Sample Type | Total Charge Passed (Coulomb) | | | | | |
| | 28-Day | | 56-Day | | 91-Day | |
	Mean	AASHTO Description	Mean	AASHTO Description	Mean	AASHTO Description
Brielmaier	1,452	Low	992	Very Low	674	Very Low
Michigan Limestone	1,699	Low	976	Very Low	658	Very Low
Martin Marietta	1,639	Low	943	Very Low	626	Very Low
Ulland	2,014	Moderate	1,154	Low	872	Very Low
New Ulm	1,566	Low	871	Very Low	601	Very Low
Barton	2,024	Moderate	1,038	Low	762	Very Low
Goldberg	2,212	Moderate	1,091	Low	926	Very Low
Fischer	1,947	Low	958	Very Low	837	Very Low
Kraemer	2,606	Moderate	1,539	Low	1,219	Low
Larson	2,532	Moderate	1,529	Low	1,236	Low
Mark	1,876	Low	1,258	Low	915	Very Low
Lanthier	1,511	Low	860	Very Low	699	Very Low

Table 5.5: RCPT results and AASHTO description of concrete specimens consist of crushed limestone coarse aggregate

Sample Type	Total Charge Passed (Coulomb)					
	28-Day		56-Day		91-Day	
	Mean	AASHTO Description	Mean	AASHTO Description	Mean	AASHTO Description
Michigan Limestone	1,699	Low	976	Very Low	658	Very Low
Ulland	2,014	Moderate	1,154	Low	872	Very Low
Goldberg	2,212	Moderate	1,091	Low	926	Very Low
Kraemer	2,606	Moderate	1,539	Low	1,219	Low
Larson	2,532	Moderate	1,529	Low	1,236	Low

Table 5.6: RCPT results and AASHTO description of concrete specimens consist of crushed aggregate of igneous and metamorphic rock origin

Sample Type	Total Charge Passed (Coulomb)					
	28-Day		56-Day		91-Day	
	Mean	AASHTO Description	Mean	AASHTO Description	Mean	AASHTO Description
Brielmaier	1,452	Low	992	Very Low	674	Very Low
Martin Marietta	1,639	Low	943	Very Low	626	Very Low
New Ulm	1,566	Low	871	Very Low	601	Very Low

Table 5.7: RCPT results and AASHTO description of concrete specimens consist of mixture of crushed aggregate and gravel of igneous and metamorphic rock origin

Sample Type	Total Charge Passed (Coulomb)					
	28-Day		56-Day		91-Day	
	Mean	AASHTO Description	Mean	AASHTO Description	Mean	AASHTO Description
Barton	2,024	Moderate	1,038	Low	762	Very Low
Fischer	1,947	Low	958	Very Low	837	Very Low
Mark	1,876	Low	1,258	Low	915	Very Low
Lanthier	1,511	Low	860	Very Low	699	Very Low
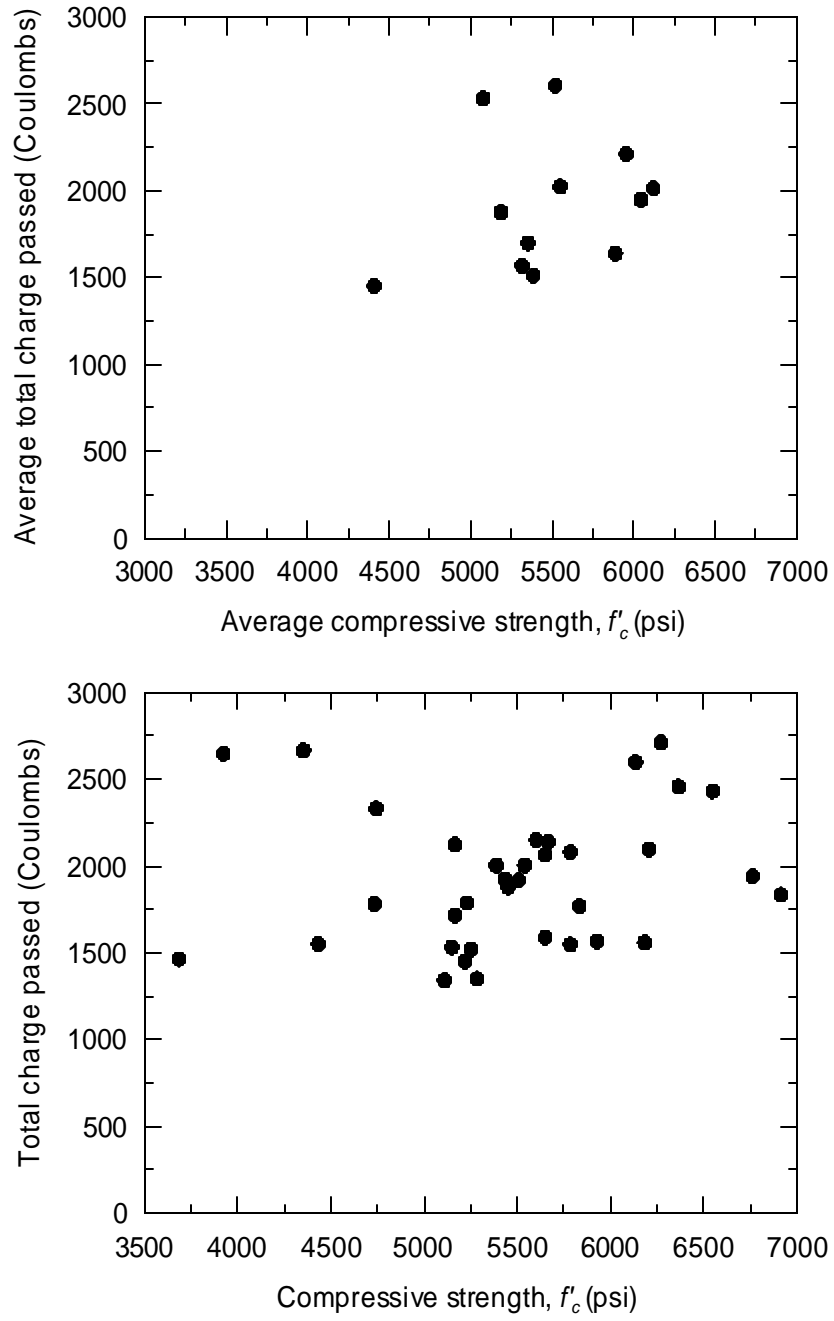
Figure 5.9: Variation of total charge passed with compressive strength of concrete specimens at 28 days of age
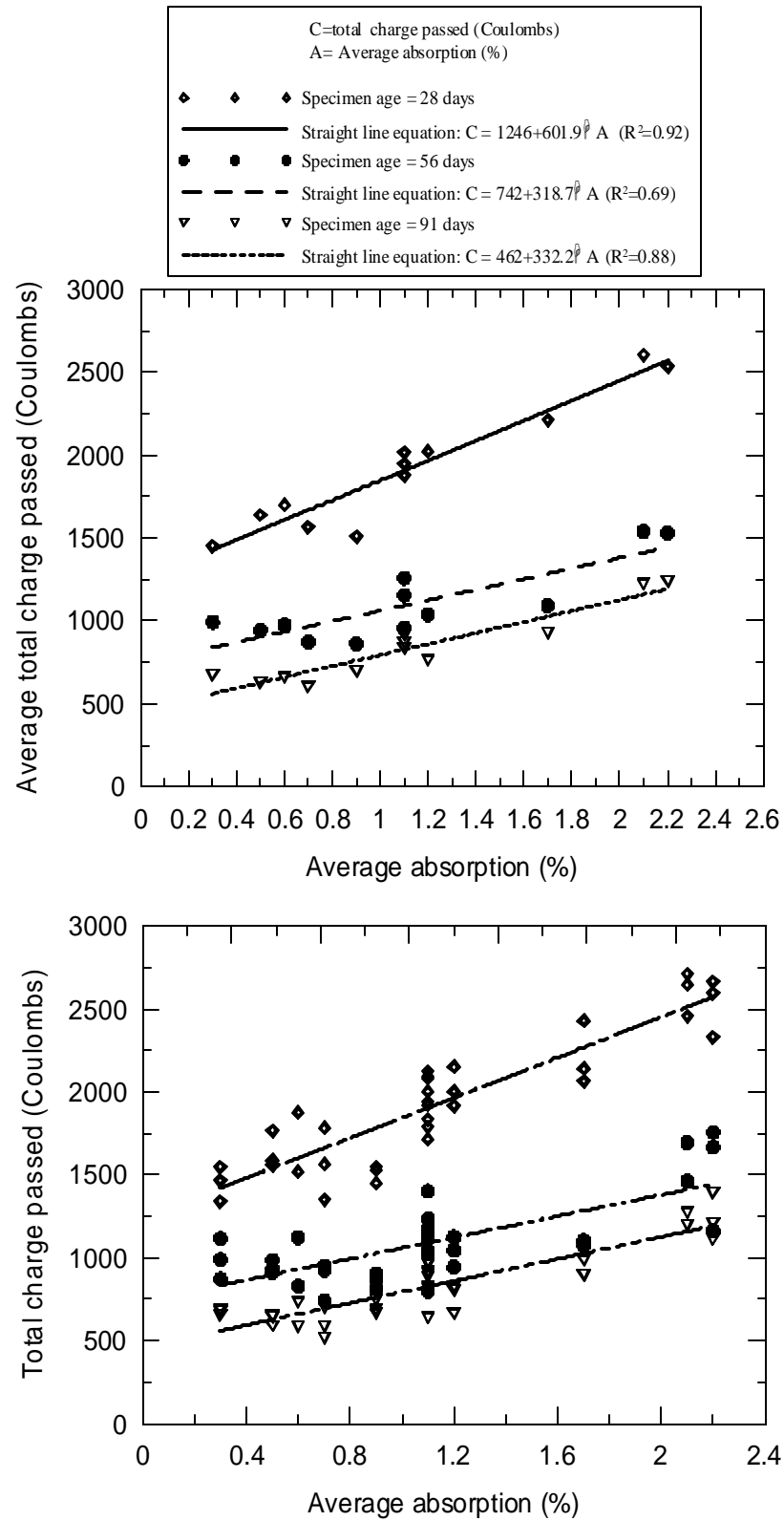
Figure 5.10: Variation of total charge passed with coarse aggregate absorption for concrete specimens at different ages.

Chapter 6
Summary and Conclusion

This research study investigated the effect of the type of coarse aggregate used in concrete on resistance to the penetration of chloride ions as indicated by the rapid chloride permeability test. The RCPT is a standard test adopted by AASHTO and ASTM and is known as AASHTO T 277 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration."

Twelve coarse aggregate types, commonly used in Mn/DOT highway construction projects, were identified and used for this study. The coarse aggregate types were subjected to laboratory testing to determine their physical properties and then used to prepare fresh concrete according to Mn/DOT specifications in which silica fume and fly ash were used. In order to characterize the concrete in terms of resistance to chloride ions penetration, concrete specimens were made of these aggregate types and were subjected to the rapid chloride permeability test at different ages; namely 28, 56, and 91 days. All mix parameters including gradation and quantities of different aggregates were held constant in different mixes. The only variable was the aggregate type.

For each aggregate type, the RCPT was performed on three specimens that were prepared from three different trial mixes. For concrete specimens tested at 28 days of age, the average total charge passed varied between 1,452 and 2,606 Coulombs, which can be described as "low" to "moderate" chloride ions penetrability, according to AASHTO T 277 designation. The "moderate" description was obtained as a result of RCPT on concrete specimens made of crushed limestone aggregate from Ulland, Goldberg, Kraemer, and Larson pit. Concrete specimens made of Michigan limestone were characterized as of "low" chloride ions penetrability according to AASHTO interpretation of RCPT results. For concrete made of crushed aggregates of igneous and metamorphic rock origin (Brielmaier, Martin Marietta, and New Ulm), all specimens were characterized as of "low" chloride ions penetrability. The concrete specimens made of aggregate that were mixture of crushed and smooth round particles of igneous rock origin were characterized as "moderate" chloride ions penetrability for Barton aggregate, and "low" chloride ion penetrability for Fischer, Mark, and Lanthier aggregates.

For all concrete specimens tested, the total charge passed decreased with time (concrete age). For example, Michigan limestone concrete specimens from trial mix #1 showed a decrease in the total charge passed from 1,878 Coulombs at age of 28 days to 732 Coulombs at age of 91 days. This is a reduction of about 61% in the initial total charge passed in approximately two months. The reason for this reduction is believed to be the continuous hydration of the cement. This reaction results in reducing the pore space and pore connectivity inside the concrete and therefore the penetration of chloride ions.

Considering all specimens at 91 days of age, the average total charge passed ranged from 601 to 1,236 Coulombs, which can be characterized as "very low" to "low" chloride ions penetrability. At age of 91 days, concrete specimens made of limestone aggregates from Kraemer and Larson pit were described as "low" chloride ions penetrability according to the AASHTO T 277 designation. Concrete specimens made of all other aggregate types were classified as "very low" chloride ions penetrability.

This report provided analyses of the RCPT results as described by AASTHO and ASTM. The characterization of the concrete made of the aggregate types used was made based on the results of the standard test procedure of AASHTO T 277.

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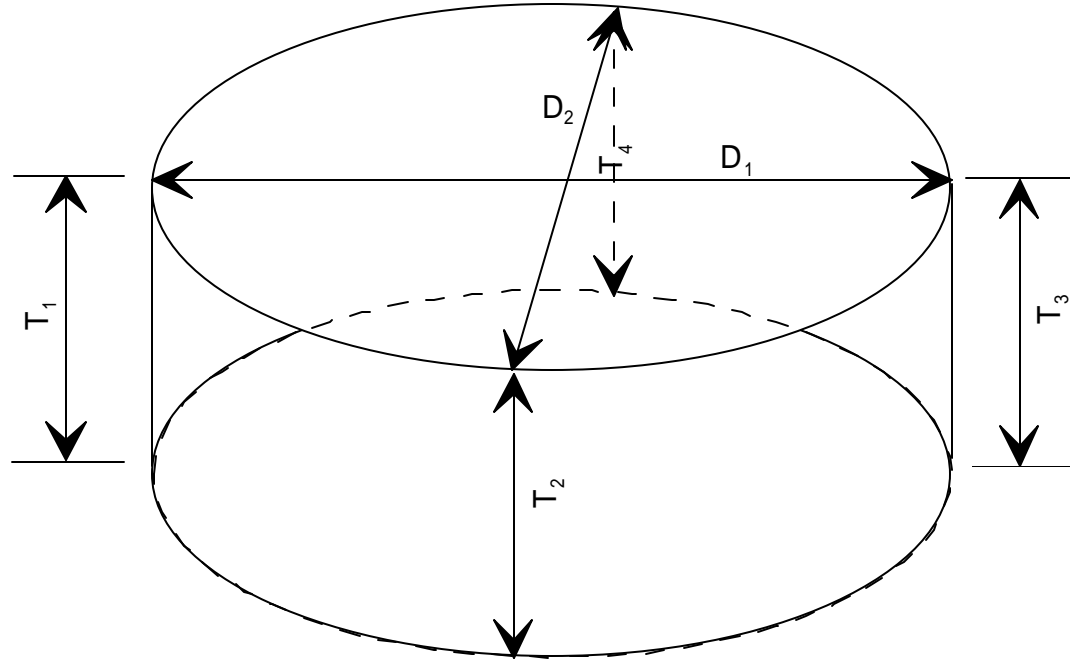
Figure A1: Measured dimensions of concrete specimens subjected to RCPT

Table A1: Diameter and thickness measurement of 28-day concrete specimens subjected to RCPT

Sample Type	Trial Mix #	Sample Position	Diameter						Thickness									
			D1		D2		Average D		T1		T2		T3		T4		Average T	
			in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm
Brielmaier	3	Top	4.04	102.6	4.04	102.5	4.04	102.6	2.08	52.8	2.09	53.1	2.05	52.1	2.07	52.5	2.07	52.6
	4	Top	4.03	102.5	4.07	103.5	4.05	103.0	2.04	51.9	2.04	51.8	2.00	50.8	2.01	51.0	2.02	51.4
	5	Top	4.03	102.3	4.03	102.5	4.03	102.4	2.03	51.6	2.01	51.0	2.00	50.9	2.01	51.0	2.01	51.1
M. Limestone	1	Top	4.01	101.8	4.05	102.9	4.03	102.4	2.04	51.7	2.06	52.3	2.03	51.5	2.05	52.1	2.04	51.9
	3	Top	3.99	101.2	4.06	103.1	4.02	102.2	1.92	48.8	1.89	48.0	1.95	49.5	2.00	50.7	1.94	49.2
Martin Marietta	1	Top	4.01	101.9	3.99	101.3	4.00	101.6	2.02	51.2	2.08	52.8	2.00	50.8	1.99	50.5	2.02	51.3
	2	Top	4.04	102.7	4.01	101.9	4.03	102.3	2.10	53.2	1.97	50.0	1.95	49.5	2.00	50.9	2.00	50.9
	3	Top	4.04	102.6	4.01	101.8	4.02	102.2	2.03	51.4	2.03	51.4	2.04	51.9	2.06	52.3	2.04	51.8
Ulland	1	Top	4.06	103.0	4.06	103.1	4.06	103.1	1.97	50.1	1.96	49.8	1.89	47.9	1.89	48.0	1.93	48.9
	2	Top	4.09	103.9	4.07	103.4	4.08	103.7	2.09	53.2	2.04	51.9	2.00	50.8	2.02	51.4	2.04	51.8
	3	Top	4.01	101.8	4.04	102.7	4.03	102.2	2.02	51.4	2.03	51.6	2.03	51.5	2.02	51.4	2.03	51.5
New Ulm	1	Top	4.04	102.5	4.01	101.9	4.02	102.2	2.07	52.5	2.03	51.5	2.00	50.8	2.07	52.5	2.04	51.8
	2	Top	4.02	102.0	4.04	102.6	4.03	102.3	2.05	52.0	2.04	51.9	2.03	51.5	2.02	51.4	2.04	51.7
	3	Top	4.07	103.5	4.01	101.8	4.04	102.6	2.04	51.7	2.02	51.4	2.03	51.6	2.02	51.4	2.03	51.5
Barton	1	Top	4.03	102.4	4.02	102.1	4.03	102.2	2.03	51.5	1.97	49.9	1.96	49.9	1.99	50.4	1.99	50.4
	2	Top	4.01	101.9	4.04	102.6	4.03	102.2	2.00	50.8	1.97	50.0	1.99	50.5	2.01	51.1	1.99	50.6
	2	Second	4.03	102.4	4.01	101.9	4.02	102.1	1.99	50.5	2.01	51.1	2.07	52.6	2.03	51.6	2.03	51.4
	2	Third	4.01	101.9	4.00	101.6	4.01	101.7	1.98	50.3	1.97	50.0	2.00	50.8	1.99	50.5	1.99	50.4
	3	Top	4.05	102.9	4.00	101.6	4.03	102.2	2.09	53.1	2.08	52.8	2.10	53.3	2.12	53.8	2.10	53.3
Goldberg	1	Top	4.04	102.6	4.02	102.1	4.03	102.4	2.04	51.8	2.01	51.1	2.09	53.1	2.03	51.6	2.04	51.9
	2	Top	4.00	101.6	4.05	102.9	4.03	102.2	2.13	54.1	2.10	53.3	2.10	53.3	2.07	52.6	2.10	53.3
	3	Top	4.01	101.9	4.05	102.9	4.03	102.4	1.95	49.5	2.05	52.1	2.00	50.8	2.02	51.3	2.01	50.9
	3	Second	4.00	101.6	4.01	101.9	4.01	101.7	1.99	50.5	1.99	50.5	1.97	50.0	2.00	50.8	1.99	50.5
	3	Third	3.99	101.3	4.01	101.9	4.00	101.6	1.97	50.0	1.98	50.3	2.00	50.8	1.99	50.5	1.99	50.4
Fischer	1	Top	4.00	101.6	4.01	101.9	4.01	101.7	2.05	52.1	2.06	52.3	2.06	52.3	1.97	50.0	2.04	51.7
	1	Second	4.02	102.1	3.98	101.1	4.00	101.6	2.04	51.8	2.05	52.1	2.04	51.8	2.03	51.6	2.04	51.8
	1	Third	4.00	101.6	3.99	101.3	4.00	101.5	2.06	52.3	2.04	51.8	2.05	52.1	2.06	52.3	2.05	52.1
	2	Top	4.20	106.7	4.01	101.9	4.11	104.3	2.03	51.6	2.00	50.8	2.11	53.6	2.09	53.1	2.06	52.3
	3	Top	4.00	101.6	4.02	102.1	4.01	101.9	1.93	49.0	1.93	49.0	1.94	49.3	1.95	49.5	1.94	49.2

Table A1 (cont.): Diameter and thickness measurement of 28-day concrete specimens subjected to RCPT

Sample Type	Trial Mix #	Sample Position	Diameter						Thickness										
			D1		D2		Average D		T1		T2		T3		T4		Average T	
			in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm
Kraemer	1	Top	4.00	101.6	4.03	102.4	4.02	102.0	1.98	50.3	2.01	51.1	2.01	51.1	2.03	51.6	2.01	51.0
	1	Second	4.01	101.9	4.00	101.6	4.01	101.7	2.05	52.1	2.08	52.8	2.08	52.8	2.07	52.6	2.07	52.6
	1	Third	4.00	101.6	4.00	101.6	4.00	101.6	2.06	52.3	2.01	51.1	2.09	53.1	2.00	50.8	2.04	51.8
	2	Top	4.02	102.1	4.03	102.4	4.03	102.2	2.08	52.8	2.05	52.1	2.08	52.8	2.06	52.3	2.07	52.5
	3	Top	4.00	101.6	4.04	102.6	4.02	102.1	2.07	52.6	2.08	52.8	2.00	50.8	2.13	54.1	2.07	52.6
Larson	1	Top	4.04	102.6	4.00	101.6	4.02	102.1	2.00	50.8	2.01	51.1	2.03	51.6	2.13	54.1	2.04	51.9
	1	Second	4.00	101.6	4.00	101.6	4.00	101.6	2.05	52.1	2.03	51.6	2.04	51.8	2.02	51.3	2.04	51.7
	1	Third	4.00	101.6	4.00	101.6	4.00	101.6	2.05	52.1	2.08	52.8	2.05	52.1	2.07	52.6	2.06	52.4
	2	Top	3.98	101.1	4.05	102.9	4.02	102.0	2.04	51.8	2.11	53.6	2.06	52.3	2.08	52.8	2.07	52.6
	3	Top	4.03	102.4	4.01	101.9	4.02	102.1	2.09	53.1	2.12	53.8	2.08	52.8	2.06	52.3	2.09	53.0
Mark	1	Top	4.01	101.9	4.01	101.9	4.01	101.9	2.08	52.8	2.10	53.3	2.07	52.6	2.06	52.3	2.08	52.8
	1	Second	4.00	101.6	4.00	101.6	4.00	101.6	2.11	53.6	2.13	54.1	2.15	54.6	2.10	53.3	2.12	53.9
	1	Third	4.00	101.6	4.01	101.9	4.01	101.7	2.10	53.3	2.15	54.6	2.15	54.6	2.13	54.1	2.13	54.2
	2	Top	4.03	102.4	4.00	101.6	4.02	102.0	2.09	53.1	2.10	53.3	2.03	51.6	2.08	52.8	2.08	52.7
	3	Top	4.02	102.1	4.01	101.9	4.02	102.0	2.12	53.8	2.13	54.1	2.12	53.8	2.15	54.6	2.13	54.1
Lanthier	1	Top	4.04	102.7	3.99	101.3	4.02	102.0	2.09	53.1	2.09	53.0	2.17	55.0	2.16	54.9	2.13	54.0
	1	Second	4.02	102.1	3.99	101.3	4.01	101.7	2.07	52.7	2.11	53.5	2.06	52.2	2.11	53.6	2.09	53.0
	1	Third	4.01	101.7	3.99	101.3	4.00	101.5	2.07	52.5	2.07	52.6	2.08	52.8	2.01	50.9	2.06	52.2
	2	Top	4.04	102.7	4.00	101.5	4.02	102.1	2.12	53.8	2.09	53.0	2.13	54.0	2.15	54.6	2.12	53.8
	3	Top	4.00	101.6	4.03	102.4	4.02	102.0	2.03	51.6	2.08	52.8	2.07	52.5	2.07	52.6	2.06	52.4

Table A2: Diameter and thickness measurement of 56-day concrete specimens subjected to RCPT

Sample Type	Trial Mix #	Sample Position	Diameter						Thickness										
			D1		D2		Average D		T1		T2		T3		T4		Average T	
			in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm
Brielmaier	3	Top	4.00	101.6	4.05	102.7	4.02	102.2	2.03	51.6	2.06	52.4	2.16	54.9	2.06	52.2	2.08	52.8
	4	Top	4.03	102.4	4.04	102.6	4.03	102.5	2.01	51.0	2.00	50.7	1.97	50.0	1.97	49.9	1.98	50.4
	5	Top	4.06	103.2	4.02	102.1	4.04	102.6	1.97	50.0	2.00	50.8	1.96	49.7	2.03	51.5	1.99	50.5
M. Limestone	1	Top	4.04	102.5	4.04	102.5	4.04	102.5	2.07	52.6	2.01	51.1	2.01	51.1	2.09	53.0	2.04	51.9
	3	Top	4.01	101.8	4.07	103.3	4.04	102.5	2.04	51.8	1.94	49.3	2.00	50.7	2.00	50.7	1.99	50.6
Martin Marietta	1	Top	4.02	102.1	4.01	101.9	4.02	102.0	1.98	50.3	2.00	50.8	1.99	50.5	1.98	50.3	1.99	50.5
	2	Top	4.00	101.6	4.01	101.9	4.01	101.7	2.03	51.6	2.04	51.8	2.03	51.6	2.00	50.8	2.03	51.4
	3	Top	4.00	101.6	4.05	102.9	4.03	102.2	2.02	51.3	2.08	52.8	2.05	52.1	2.05	52.1	2.05	52.1
Ulland	1	Top	4.03	102.4	4.02	102.1	4.03	102.2	2.01	51.1	2.06	52.3	2.05	52.1	1.91	48.5	2.01	51.0
	2	Top	4.00	101.6	4.03	102.4	4.02	102.0	2.02	51.3	2.00	50.8	2.03	51.6	2.13	54.1	2.05	51.9
	3	Top	4.03	102.4	4.00	101.6	4.02	102.0	2.07	52.6	2.02	51.3	1.97	50.0	1.97	50.0	2.01	51.0
New Ulm	1	Top	4.01	101.9	4.03	102.4	4.02	102.1	1.97	50.0	2.05	52.1	1.97	50.0	2.13	54.1	2.03	51.6
	2	Top	4.03	102.2	4.01	102.0	4.02	102.1	2.07	52.6	2.08	52.7	2.07	52.5	2.07	52.6	2.07	52.6
	3	Top	4.02	102.2	4.02	102.2	4.02	102.2	2.02	51.4	2.02	51.4	2.12	53.7	2.11	53.6	2.07	52.5
Barton	1	Top	4.03	102.4	4.01	101.9	4.02	102.1	2.08	52.9	2.09	53.2	2.04	51.9	2.11	53.6	2.08	52.9
	2	Top	4.03	102.4	4.04	102.7	4.04	102.5	2.02	51.3	2.06	52.2	2.11	53.5	2.04	51.7	2.05	52.2
	3	Top	4.06	103.1	3.99	101.4	4.03	102.3	2.02	51.2	2.16	54.8	2.02	51.4	2.02	51.2	2.05	52.2
Goldberg	1	Top	4.04	102.6	4.01	101.9	4.03	102.3	2.12	53.7	2.09	53.1	2.11	53.6	2.15	54.5	2.12	53.8
	2	Top	4.06	103.2	3.99	101.3	4.03	102.3	2.02	51.3	2.09	53.2	2.01	51.1	2.03	51.6	2.04	51.8
	3	Top	4.04	102.5	4.01	101.9	4.02	102.2	2.08	52.9	2.09	53.1	2.11	53.7	2.08	52.8	2.09	53.1
	3	Second	4.03	102.3	4.02	102.1	4.02	102.2	2.15	54.7	2.16	54.9	2.16	54.8	2.17	55.2	2.16	54.9
	3	Third	3.98	101.2	4.00	101.6	3.99	101.4	2.04	51.7	2.06	52.3	2.08	52.9	2.05	52.1	2.06	52.2
Fischer	1	Top	4.05	102.9	4.00	101.6	4.03	102.2	2.07	52.5	2.11	53.5	2.07	52.5	2.04	51.8	2.07	52.6
	2	Top	4.02	102.0	4.03	102.4	4.02	102.2	1.95	49.6	1.94	49.2	2.04	51.7	2.06	52.3	2.00	50.7
	3	Top	4.03	102.4	4.01	101.9	4.02	102.1	2.06	52.2	2.06	52.3	2.11	53.5	2.11	53.6	2.08	52.9

Table A2 (cont.): Diameter and thickness measurement of 56-day concrete specimens subjected to RCPT

Sample Type	Trial Mix #	Sample Position	Diameter						Thickness										
			D1		D2		Average D		T1		T2		T3		T4		Average T	
			in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm
Kraemer	1	Top	4.00	101.7	4.06	103.0	4.03	102.3	2.13	54.2	2.11	53.5	2.03	51.5	2.04	51.8	2.08	52.7
	1	Second	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1	Third	4.01	102.0	4.01	101.9	4.01	101.9	2.13	54.1	2.16	54.7	2.15	54.5	2.13	54.2	2.14	54.4
	2	Top	4.07	103.5	4.00	101.6	4.04	102.5	1.98	50.2	1.95	49.5	2.03	51.6	2.04	51.7	2.00	50.7
	3	Top	4.05	102.9	4.03	102.4	4.04	102.7	2.14	54.3	2.11	53.6	2.12	53.9	2.16	54.9	2.13	54.2
Larson	1	Top	4.02	102.1	4.01	102.0	4.02	102.0	2.11	53.5	2.11	53.5	2.12	53.9	2.07	52.6	2.10	53.4
	2	Top	4.00	101.6	4.03	102.4	4.02	102.0	1.93	48.9	1.96	49.9	2.04	51.8	2.01	51.1	1.99	50.4
	3	Top	4.04	102.6	4.01	101.9	4.02	102.2	2.06	52.2	2.05	51.9	2.02	51.3	2.05	52.2	2.04	51.9
Mark	1	Top	4.01	101.9	4.01	101.8	4.01	101.9	2.03	51.6	2.06	52.4	2.11	53.5	2.12	53.9	2.08	52.8
	2	Top	4.05	103.0	3.98	101.2	4.02	102.1	2.13	54.2	2.07	52.6	2.10	53.4	2.11	53.6	2.10	53.5
	3	Top	4.02	102.2	4.04	102.6	4.03	102.4	2.12	53.8	2.09	53.2	2.12	53.8	2.09	53.0	2.10	53.4
Lanthier	1	Top	4.02	102.1	4.03	102.4	4.03	102.2	2.11	53.5	2.05	52.1	2.01	51.1	2.03	51.5	2.05	52.0
	2	Top	4.01	101.9	4.03	102.3	4.02	102.1	2.14	54.2	2.08	52.9	2.11	53.6	2.10	53.4	2.11	53.5
	3	Top	4.05	102.9	3.99	101.4	4.02	102.2	2.06	52.2	2.02	51.2	2.00	50.9	2.01	51.1	2.02	51.3
Waukesha	1	Top	4.01	101.9	4.02	102.2	4.02	102.0	1.86	47.2	1.89	48.0	1.95	49.6	1.98	50.3	1.92	48.8
	2	Top	4.02	102.1	4.03	102.4	4.03	102.2	2.03	51.6	2.07	52.5	2.00	50.7	1.98	50.3	2.02	51.3

Table A3: Diameter and thickness measurement of 91-day concrete specimens subjected to RCPT

Sample Type	Trial Mix #	Sample Position	Diameter						Thickness									
			D1		D2		Average D		T1		T2		T3		T4		Average T	
			in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm
Brillmeir	3	Top	4.01	101.9	4.01	101.9	4.01	101.9	2.15	54.5	2.11	53.5	2.11	53.7	2.16	54.9	2.13	54.1
	4	Top	4.01	101.7	4.05	102.7	4.03	102.2	2.07	52.7	2.06	52.4	1.96	49.8	2.00	50.9	2.02	51.4
	5	Top	4.02	102.1	4.03	102.2	4.02	102.1	2.11	53.6	2.02	51.2	2.02	51.2	2.08	52.9	2.06	52.2
M. Limestone	1	Top	4.04	102.7	4.00	101.7	4.02	102.2	2.12	53.8	2.09	53.1	2.10	53.4	2.15	54.6	2.11	53.7
	3	Top	4.04	102.5	4.04	102.5	4.04	102.5	2.07	52.5	2.13	54.2	2.13	54.1	2.12	53.9	2.11	53.7
Martin Marietta	1	Top	4.03	102.3	4.03	102.3	4.03	102.3	2.12	53.9	2.12	53.7	2.18	55.5	2.18	55.4	2.15	54.6
	2	Top	4.02	102.2	4.01	101.9	4.02	102.0	2.05	52.1	2.07	52.6	2.06	52.3	2.05	52.1	2.06	52.3
	3	Top	4.01	101.9	4.02	102.2	4.02	102.1	2.01	51.1	1.99	50.5	2.08	52.8	2.08	52.9	2.04	51.8
Ulland	1	Top	4.01	101.8	4.04	102.7	4.03	102.2	2.00	50.9	2.05	52.1	2.03	51.5	2.00	50.7	2.02	51.3
	2	Top	4.03	102.5	4.01	101.9	4.02	102.2	2.04	51.9	2.02	51.4	2.06	52.2	2.11	53.7	2.06	52.3
	3	Top	4.00	101.6	4.03	102.4	4.02	102.0	2.11	53.5	2.05	52.1	2.01	51.1	2.03	51.5	2.05	52.0
New Ulm	1	Top	4.03	102.2	4.02	102.2	4.02	102.2	1.96	49.8	1.97	50.1	2.00	50.9	2.03	51.6	1.99	50.6
	2	Top	4.01	101.9	4.03	102.5	4.02	102.2	2.04	51.7	2.07	52.6	1.93	48.9	1.97	50.0	2.00	50.8
	3	Top	4.03	102.2	4.01	101.8	4.02	102.0	2.02	51.2	1.98	50.3	2.07	52.6	2.06	52.4	2.03	51.6
Barton	1	Top	4.04	102.7	4.01	101.8	4.02	102.2	2.01	51.0	2.08	52.8	2.07	52.6	2.09	53.0	2.06	52.4
	2	Top	4.04	102.7	4.03	102.4	4.04	102.5	2.05	52.1	2.08	52.9	2.02	51.3	2.07	52.7	2.06	52.2
	3	Top	4.02	102.1	4.01	101.9	4.02	102.0	2.01	51.1	2.03	51.5	2.03	51.5	1.97	50.1	2.01	51.0
Goldberg	1	Top	4.00	101.6	4.04	102.5	4.02	102.1	2.03	51.5	2.02	51.4	2.01	51.0	2.00	50.7	2.01	51.1
	2	Top	4.01	101.9	4.02	102.2	4.02	102.0	1.98	50.3	1.88	47.8	1.93	49.0	1.96	49.8	1.94	49.2
	3	Top	4.02	102.0	4.03	102.3	4.02	102.1	1.99	50.4	1.96	49.8	2.00	50.9	1.97	50.1	1.98	50.3
Fischer	1	Top	4.08	103.6	4.02	102.2	4.05	102.9	1.92	48.9	1.92	48.7	1.96	49.8	1.97	50.1	1.94	49.4
	2	Top	4.03	102.4	4.00	101.7	4.02	102.0	2.02	51.4	1.98	50.3	1.92	48.6	2.00	50.9	1.98	50.3
	3	Top	4.04	102.6	3.99	101.4	4.02	102.0	1.93	49.1	1.94	49.4	1.94	49.3	2.02	51.4	1.96	49.8

Table A3 (cont.): Diameter and thickness measurement of 91-day concrete specimens subjected to RCPT

Sample Type	Trial Mix #	Sample Position	Diameter						Thickness									
			D1		D2		Average D		T1		T2		T3		T4		Average T	
			in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm
Kraemer	1	Top	4.05	102.8	3.99	101.3	4.02	102.1	2.03	51.4	2.04	51.9	2.04	51.7	2.12	53.8	2.06	52.2
	2	Top	4.03	102.4	4.01	101.7	4.02	102.1	1.98	50.4	2.03	51.6	2.00	50.9	2.02	51.4	2.01	51.1
	3	Top	4.05	102.9	3.99	101.4	4.02	102.2	1.99	50.4	1.99	50.4	2.00	50.7	1.98	50.4	1.99	50.5
Larson	1	Top	4.02	102.0	4.02	102.2	4.02	102.1	2.02	51.3	2.00	50.8	2.05	52.0	2.06	52.4	2.03	51.6
	2	Top	4.02	102.0	4.02	102.2	4.02	102.1	1.91	48.5	2.01	51.0	1.99	50.4	1.90	48.3	1.95	49.5
	3	Top	4.04	102.7	4.00	101.5	4.02	102.1	2.01	51.1	2.04	51.7	1.96	49.8	1.97	50.1	2.00	50.7
Mark	1	Top	4.04	102.6	4.00	101.6	4.02	102.1	2.05	52.0	2.01	51.0	2.01	51.0	2.10	53.4	2.04	51.8
	2	Top	4.03	102.2	4.01	101.8	4.02	102.0	1.98	50.2	1.99	50.5	2.02	51.3	2.00	50.7	2.00	50.7
	3	Top	4.03	102.3	4.01	101.8	4.02	102.1	1.97	49.9	1.94	49.4	1.96	49.7	2.01	51.1	1.97	50.0
Lanthier	1	Top	4.01	101.8	4.03	102.4	4.02	102.1	2.00	50.8	1.95	49.4	1.99	50.4	2.02	51.2	1.99	50.5
	2	Top	3.99	101.2	4.05	102.9	4.02	102.0	1.94	49.3	1.97	49.9	2.04	51.9	1.94	49.3	1.97	50.1
	3	Top	4.00	101.6	4.05	102.8	4.02	102.2	2.01	51.1	2.01	51.1	2.08	52.8	2.06	52.2	2.04	51.8
Waukesha	1	Top	4.03	102.4	4.03	102.3	4.03	102.3	2.09	53.1	1.99	50.5	2.01	50.9	2.06	52.3	2.04	51.7
	2	Top	4.02	102.0	4.02	102.2	4.02	102.1	2.00	50.9	1.99	50.6	2.04	51.8	2.02	51.4	2.01	51.1