# Wisconsin Highway Research Program

# Effects of Ground Granulated Blast Furnace Slag in Portland Cement Concrete (PCC)- Expanded Study

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# Effects of Ground Granulated Blast Furnace Slag in Portland Cement Concrete – Expanded Study


# Final Report

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# Disclaimer

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16. Abstract

This research examined the properties of concrete containing grade 120 slag cement at replacement levels of 0%, 30%, and 50%. The primary concrete properties studied were compressive strength, split-tensile strength, and deicer scaling resistance. Material variations included four sources of ordinary portland cement and two types of coarse aggregate. Strength properties were studied at room temperature and 40°F mix and curing conditions. Deicer scaling resistance was studied for concrete cured under six curing conditions. Carbonation of concrete cured under these six conditions was also investigated. It was determined that concrete containing 30% and 50% replacement of OPC with grade 120 slag cement had a decreased initial compressive and tensile strength compared to OPC concrete. However, by 14 days, the grade 120 slag cement concrete strength equaled or surpassed that of OPC concrete. Compared to OPC concrete, the time to reach 3000psi traffic opening strength was delayed by 1 to 2 days for 30% replacement and by 3 to 4 days for 50% replacement. Deicer scaling resistance decreased as the level of slag cement replacement increased. Curing methods which limited carbonation produced concrete with the highest level of scaling resistance. Air-cured concrete had higher scaling resistance than concrete cured with commercial curing compounds. The scaling resistance of all grade 120 slag cement concrete was within acceptable limits. Variations in portland cement source caused changes in strength and scaling resistance properties. Variation in coarse aggregate influenced compressive and tensile strengths but did not influence the deicer scaling resistance. Comparisons with previous research on grade 100 slag are included.

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# Executive Summary

## *Project Summary*

Slag cement[1] is a cementitious replacement material that has been used in United States concrete design since the early 1900s (Slag Cement Association, 2002). Slag cement is a byproduct of the iron-making process and is composed primarily of silica and calcium. In fine particle form, slag cement displays cementitious qualities similar to those of ordinary portland cement (OPC). Slag cement can therefore be substituted for OPC in a wide range of equal mass replacement ratios. Because the root blast-furnace slag material would otherwise be discarded after separation from molten iron, the U.S. Environmental Protection Agency has designated slag cement as a "recovered material." Agencies are required by Executive Order 13101 to use high levels of recovered materials whenever possible (United States Environmental Protection…, 1998). Therefore, there is incentive to use slag cement in the state of Wisconsin. Because the stoichiometry of portland cement hydration varies with different additives and field conditions, replacement of portland cement with slag cement cannot be presumed to yield equivalent concrete. This research was directed at examining the performance slag cement with materials commonly used in Wisconsin paving projects. This project was a continuation of an in-depth study of slag cement concrete for highway pavement applications in the state of Wisconsin. A previous phase examined the performance grade 100 slag cement concrete. The objective of the current research project was to quantify the strength development and deicer scaling resistance of grade 120 slag cement concrete over a range of portland cement sources, aggregates and curing conditions used in Wisconsin.

## *Background*

Strength gain is a critical parameter in the evaluation of the performance of concrete. Strength gain is not only an inherently important property, but it also indicates the quality of the overall cement matrix. Using slag cement as a replacement material for OPC changes the rate of strength gain because the hydration properties of slag cement are different from OPC. Slag cement is a latent hydraulic material, meaning that with use of this material, the rate of strength gain will be lower when compared to OPC concrete. Conflicting data exists, however, as to if and when the strength of slag cement eventually "catches up" to similar concrete containing 100% OPC. Several studies have found that slag cement concretes with 30% to 65% replacement were stronger than OPC concretes after 7 to 10 days (Hogan and Meusel 1981, Meusel and Rose 1983). Fernanzez and Malhotra (1990) show that 25% slag cement replacement mix strengths are comparable to OPC at 28 days, but that 50% slag cement replacement mix strengths are lower than OPC

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[1] Slag cement is often referred to as "ground granulated blast-furnace slag" (GGBFS). As requested in 2001 by slag cement manufacturers and the Slag Cement Association, the American Concrete Institute officially reviewed and changed the terminology from GGBFS to slag cement (ACI Committee 233, 2004). The term slag cement will be used throughout this paper when referring to finely-ground granulated blast-furnace slag.

at all ages.  Malhotra (1983) reports that for slag cement blends of 25%, 45%, and 65%, strengths are generally less than OPC concretes at all ages.  The tensile to compressive strength ratio is also important in highway pavement design, and similar conflicting reports exist on this parameter.  A major portion of this study was devoted to investigation of the compressive and split-tensile strengths of grade 120 slag cement concrete with replacement levels for OPC of 30% and 50%.

There is similar controversy over the deicer scaling resistance of concrete containing slag cement.  This parameter is especially significant in highway pavement applications, as roadways are often exposed to freezing and thawing of water that collects on road surfaces after deicing agents have been applied.  One study reported only a small difference in the level of deicer scaling that occurred in slag cement concrete versus OPC concrete (Dubovoy, et al, 1986).  Afrani and Rogers (1994), on the other hand, recorded much greater scaling loss for concrete with high slag cement replacement compared to 100% OPC concrete.  Also noted was a difference in deicer scaling resistance apparently due only to a small change in testing methods (Afrani and Rogers, 1994).  In addition, evaluation of deicer scaling resistance is difficult in the United States because no standard exists which sets quantitative limits on the definition of "good" and "bad" performance.  In those cases where slag cement was found to be detrimental to the scaling resistance of concrete, researchers found it difficult to provide a clear explanation as to how slag cement caused the new behavior.  Some authors (Stark and Ludwig, 1997; Copuraglu, 2004) have investigated an explanation and found that carbonation is a potential link between slag cement and low deicer scaling resistance.  This study quantitatively investigated the deicer scaling resistance of grade 120 slag cement concrete with replacement levels for OPC of 30% and 50%.  Carbonation of the concrete was also studied to determine if a link between the two parameters exists.


### *Research Plan*

This study aimed to determine variations in performance for grade 120 slag cement concrete using a range of materials common to Wisconsin highway pavement construction.  The research plan consisted of three tasks:

> Task 1:  Assess the variability of slag cement over a period of one year;
> Task 2:  Assess the strength gain (both compressive and split-tensile strengths) and air void development under various conditions; and
> Task 3:  Assess the deicer scaling resistance under various conditions.

For Task 1, materials included four sources of Type I OPC, two types of coarse aggregate, and slag cement replacement levels of 0%, 30%, and 50% for a total of 24 different types of concrete.  In addition, one source of OPC was studied with both aggregates and all replacement levels at a mixing and curing temperature of 40°F.  Strength tests were conducted at six ages.

For Task 2, materials included two sources of Type I OPC, two types of coarse aggregate, and slag cement replacement levels of 0%, 30%, and 50% for a total of 12 different types

of concrete.  In addition, six curing methods were studied for each type of concrete. Carbonation was also measured at five ages for all concrete mixed in Task 2.

The materials mentioned above were selected based on their pertinence to Wisconsin paving applications.  These materials included:
1. Type I portland cement from four manufacturers – Holcim, Cemex, Dixon-Marquette, and Lafarge (in no particular order);
2. ¾-inch limestone crushed rock coarse aggregate from South Central Wisconsin;
3. ¾-inch igneous river stone coarse aggregate from Northwestern Wisconsin;
4. Natural river sand fine aggregate from South Central Wisconsin;
5. Grade 120 slag cement (Lafarge North America);
6. Vinsol resin air-entraining agent (SikaLatex);
7. Wax curing compound (W. R. Meadows 1600 white series); and
8. AMS (alphamethylstyrene) curing compound (W. R. Meadows 2200 white series).

### Research Process

The methodologies of the three tasks in the research plan were carried out according to accepted procedures.  In some cases, modifications were made to enhance the level of meaningful data, and these modifications are discussed in the body of the report.  Task 1 involved the assessment of variability of grade 120 slag cement.  Samples of the material were collected once per month from a local ready-mix supplier.  Testing included chemical analysis (ASTM C114), Blaine fineness (ASTM C204), and slag activity index (ASTM C989).  Task 2 testing included compressive strength (ASTM C617 and C39), split-tensile strength (ASTM C496), and hardened air void analysis (ASTM C457).  Task 3 testing included deicer scaling resistance according to a modified ASTM C 672 and carbonation testing (RILEM CPC18).

For all concrete mixed for Tasks 2 and 3, a water-cementitious material ratio (w/cm) of 0.45 was used.  The mix proportions for all concrete was based on Wisconsin Department of Transportation Grade A and Grade A-S mix designs.  The target fresh air content for all concrete was 6.0%±0.5%.  Fresh concrete testing included slump (ASTM C143), unit weight (ASTM C138), and fresh air content (ASTM C231).  For concrete mixed in Task 3, six curing methods were employed.  The six methods included air curing in the laboratory, wet curing according to ASTM C672, use of two different commercial curing compounds, and use of two different carbonation mitigation methods.

Primary data collected in Task 1 included chemical compositions and fineness of the slag cement and portland cements and hydraulic activation indices for cement and slag cement combinations.  In Task 2, compressive strength and split-tensile strength were measured at concrete ages of 3, 7, 14, 28, 56, and 365 days.  For concrete mixed and cured at 40°F, test ages were limited to 3, 7, 14, 28, and 56 days.  All strength tests were based on five test replicates.  The strength testing considered one brand of Grade 120 slag cement at 0%, 30%, and 50% replacement levels, four brands of Type I portland cement, and two types of coarse aggregate.  40°F testing only utilized one brand of OPC.  In Task 3,

deicer scaling testing began after a curing period of 28 days. Tests were conducted after every fifth freeze-thaw cycle and continued until 60 freeze-thaw cycles were completed. Scaling material was collected and weighed after each test. The scaling resistance testing considered one brand of Grade 120 slag cement at 0%, 30%, and 50% replacement levels, two brands of Type I portland cement, two types of coarse aggregate, and six different curing regimes. All deicer scaling tests were based on three test replicates.

### Findings and Conclusions
The performance of grade 120 slag cement concrete was generally comparable to OPC concrete in most cases. It was found, however, that variations in slag cement replacement level, coarse aggregate type, OPC brand, and mixing and curing conditions play a large role in the performance of hardened concrete.

The results of Task 1 suggest that the overall variability of monthly slag cement shipments from the local supplier was not high. However, it was concluded that slight variations in the major chemical components of the slag cement (for instance calcium and silica) can be traced to changes in the slag activity index and thus a reduction in rate of strength gain.

Based on testing in Task 2, it was found that variations in slag cement replacement level, coarse aggregate type, and OPC brand affected the rate of strength gain and final strength for both compressive and split-tensile concrete testing. Most significantly, reductions in the rate of strength gain caused by increasing the slag cement replacement level led directly to longer waiting times before the highway opening strength of 3000psi was achieved. A summary of time to achieve 3000 psi compressive strength follows:
- 0% slag cement: range of 3 to 4 days; average 3 days with limestone coarse aggregate and 4 days with igneous coarse aggregate
- 30% slag cement: range of 3 to 8 days; average 4 days with limestone coarse aggregate and 6 days with igneous coarse aggregate
- 50% slag cement: range of 5 to 9 days; average 6 days with limestone coarse aggregate and 8 days with igneous coarse aggregate
- At 40°F: average 7 days with 0% slag cement, average 12 days with 30% slag cement, and average 17 days with 50% slag cement

It was found that use of grade 120 slag cement does not have a significant effect on the tensile-compressive strength ratios compared to OPC concrete. It was also found that the effects of slag cement replacement on the actual split-tensile strength values were similar to the effects on compressive strength.

Results from Task 3 indicate that variations in slag cement replacement level, OPC brand, and curing method affected the level of deicer scaling resistance of the concrete. As expected, an increase in slag cement replacement resulted in a decrease in deicer scaling resistance. The method of curing also had a pronounced effect on scaling loss, and it was concluded that methods which reduce carbon dioxide exposure (and thus reduce carbonation) resulted in the most resistant concrete. Methods which produced concrete with the least resistance to scaling loss included wet curing and the two

commercial curing compounds.  Overall, however, concrete in this study performed well with respect to several international standards.  Cumulative scaling loss after 60 freeze-thaw cycles were in the following ranges:

- 0% slag cement:  1.7 $g/m^2$ to 327 $g/m^2$
- 30% slag cement:  1.5 $g/m^2$ to 363 $g/m^2$
- 50% slag cement:  3.4 $g/m^2$ to 583 $g/m^2$

In summary, grade 120 slag cement is a viable material for use in highway pavement concrete design.  While variations in mix materials and curing conditions cause changes in the performance of the hardened concrete, many options exist for combinations of materials that are successful with grade 120 slag cement at replacement levels up to 50%.

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## 1. Problem Statement

Federal transportation directives encourage the use of by-product materials and mandate open and unrestricted competition for alternative cementitious materials. The Environmental Protection Agency listed slag cement (ground granulated blast furnace slag, or GGBFS) as a recyclable material in the Federal Register in 1995. Listing on the Register allows slag cement to be used in meeting the minimum recyclable material content on many federally funded projects. The federal directive essentially mandates that the marketplace must be open for listed materials and limiting use of products such as slag cement cannot be done without strong cause. The stoichiometry of cementitious hydration of slag cementis neither understood nor sufficiently predictable to ensure performance of the concrete for a variety of weather and mix conditions. Therefore without supporting research, the use of alternative cementitious materials presents a significant risk to the Wisconsin concrete infrastructure.

## 2. Objectives and Scope of Study

According to ASTM C989, slag cement is classified into three grades: grade 80, grade 100, and grade 120. Increasing grade indicates a higher level of hydraulic activity when mixed with ordinary portland cement (OPC) and water. In the previous phase of this study, the properties of concrete made with partial replacement of OPC with grade 100 slag cement was investigated (Cramer and Sippel 2005). In the current phase, grade 120 concrete was studied.

The objective of this phase of the study was to determine strength and deicer salt scaling resistance properties of concrete with partial slag cement replacement for OPC. The research plan included the effects of Type I portland cement from four different manufacturers, three grade 120 slag cement replacement levels, and two types of coarse aggregate. In addition, source variability of slag cement was investigated.

The research plan consisted of three tasks:

> Task 1: Assess the variability of slag cement composition by monitoring supply shipments into Wisconsin. Characterization tests included: chemical composition, Blaine fineness, slag activity with OPC.
> Task 2: Assess the strength gain and air void development with different materials and temperatures. Testing included compressive strength, split-cylinder tensile strength, air void analysis, and shrinkage.
> Task 3: Assess the deicer scaling resistance of slag cement concrete with different materials and curing compounds.

The strength gain and deicer scaling tests used grade 120 slag cement as replacement for OPC at levels of 0% (100% OPC; control mix), 30%, and 50%. Thirty mixes were evaluated in Task 2 regarding compressive and tensile strength gain. Twelve mixes were evaluated in Task 3 regarding deicer scaling. Freeze-thaw testing for the deicer scaling

tests followed a modified ASTM C672 test procedure.  In addition, the effect of carbonation on deicer scaling resistance was investigated.


## 3.  Background

Hydration of the cementitious materials in concrete is largely responsible for the hardened concrete properties.  The hydration of slag cement is different from that of OPC, although the final hydration products are similar.  Hydration of slag cement occurs more slowly than that of OPC.  Strength gain in concrete is often proportional to rate of hydration; however both short-term and long-term compressive strength data for slag cement concrete does not provide a firm conclusion regarding strength gain (Hogan and Meusel, 1981; Meusel and Rose, 1983; Fernanzez and Malhotra, 1990; Malhotra, 1983).  Tensile strength of slag cement concrete has been found to be as good as or better than OPC concrete (Desai, 2004; Wainwright and Tolloczko, 1986; Malhotra, 1983).  Environmental conditions have also been found to affect strength properties.  Slag cement concrete mixed in cold conditions (below 20°C) had lower strength development at all ages compared to slag cement concrete mixed at 20°C (Wimpenney et al., 1989; Eren, 2002; Cramer and Sippel, 2005).

Concrete used in Midwest regional highway pavement applications must demonstrate adequate resistance to deicing salt agents applied to roadways during winter months.  It has been found that replacing OPC with slag cement leads to decreased deicer scaling resistance in laboratory tests and increased wear on the concrete surface (Stark and Ludwig, 1997; Afrani and Rogers, 1994).  It has been proposed that concrete carbonation causes a decrease in the deicer scaling resistance performance (Stark and Ludwig, 1997; Çopuroğlu et al., 2004).  Carbonation occurs to a greater extent in slag cement concrete than in OPC concrete due to greater consumption of calcium hydroxide during hydration (Sulapha et al., 2003).

A comprehensive literature review of pertinent research was conducted on research published up to 2006.  The main features of this review were mentioned above.  A bibliography of these articles can be found in Appendix I, and synthesis of the literature is presented in Appendix II.


## 4.  Methodology and Testing Regime

### 4.1  General

The methodologies to complete the three tasks involved in this research plan followed accepted procedures with some modifications to expand and enhance the value of the data.  Task 1 tests involved characterization of the variability of slag cement from a local supplier.  Twelve samples were collected from the supplier over a period of one year.  The tests conducted in Task 1 are summarized in Table 1.  Task 2 testing included air dry shrinkage, hardened air void analysis, compressive strength, and split-tensile strength as

shown in Table 2.  Thirty mixes were completed for Task 2.    Task 3 testing involved the measurement of deicer scaling resistance.  In addition, carbonation was measured for concrete mixed in Task 3.  Two of the four portland cement brands studied in Task 2 were used in Task 3.  Twelve mixes were completed for Task 3.  Four or six curing regimes were tested in each mix.  The tests conducted in Task 3 are summarized in Table 3.  The curing regimes are summarized in Table 4.

For both Tasks 2 and 3, the mix variables were cement brand, slag cement replacement level, and coarse aggregate type.  Curing temperature was also a variable for Task 2 concrete.  For both Tasks 2 and 3, a water to cementitious material ratio (w/cm ratio) of 0.45 was employed with a target fresh air content of 6.0%±0.5%.

**Table 1.**  Summary of Tests Conducted in Task 1

| Test | Number of Tests | Applicable Standard |
|---|---|---|
| Blaine Fineness | Once per sample | ASTM C204 |
| Chemical Analysis | Once per sample | ASTM C114 |
| Slag Activity | Once per sample | ASTM C989 |

**Table 2.**  Summary of Tests Conducted in Task 2

| Test | Number of Tests | Applicable Standard | Curing Method | Concrete Age (days) |
|---|---|---|---|---|
| Slump | One per batch | ASTM C143 | N/A | 0 (fresh) |
| Plastic Air Content | One per batch | ASTM C231 | N/A | 0 (fresh) |
| Unit Weight | One per batch | ASTM C138 | N/A | 0 (fresh) |
| Air Void Analysis | One per mix | ASTM C457 | Moist Cured 14 days; then 50% RH and 73 F | N/A |
| Air Dry Shrinkage | Three per mix | ASTM C490, ASTM C157 modified | Moist Cured 14 days; then 50% RH and 73 F | up to 120 days |
| Compressive Strength | Five per mix at six ages | ASTM C617, ASTM C39 | Moist Cured until test age | 3, 7, 14, 28, 56, 365 |
| Split-Tensile Strength | Five per mix at six ages | ASTM C496 | Moist Cured until test age | 3, 7, 14, 28, 56, 365 |

**Table 3.**  Summary of Tests Conducted in Task 3

| Test | Number of Tests | Applicable Standard | Curing Method | Concrete Age (days) |
|------|-----------------|---------------------|---------------|---------------------|
| Slump | One per batch | ASTM C143 | N/A | 0 (fresh) |
| Plastic Air Content | One per batch | ASTM C231 | N/A | 0 (fresh) |
| Unit Weight | One per batch | ASTM C138 | N/A | 0 (fresh) |
| Deicer Scaling Resistance | 12 per sample; 12 to 18 samples per mix | ASTM C672 | See Table 4 | 28 - 88 |
| Carbonation | 5 per sample; 4 to 6 samples per mix | RILEM CPC18 | See Table 4 | 14, 28, 40, 60, 80 |

**Table 4.**  Summary Curing Methods Used in Task 3

| Curing I.D. | Description | Duration |
|-------------|-------------|----------|
| Air | Laboratory conditions (approx. 70° F and 50% R.H.) | 27 days |
| Soda Lime[1] | Covered with pellets of soda lime (carbon dioxide absorber) | 26 days |
| Plastic Wrap[2] | Wrapped in layers of impermeable plastic to inhibit carbon dioxide exposure | 26 days |
| Wet | Moist conditions (70° F and 100% R.H.) | 14 days |
| | Laboratory conditions (approx. 70° F and 50% R.H.) | 14 days |
| Wax | Coated with wax-based commercial curing compound 1 hour after casting | 28 days |
| AMS | Coated with AMS (alphamethylstyrene) commercial curing compound 1 hour after casting | 28 days |

## 4.2  Materials

Materials were selected based on their pertinence to Wisconsin concrete paving operations. The following materials were used:[3]

1. Type I cement from four manufacturers: Cemex, Dixon-Marquette, Holcim, and Lafarge (in no particular order)
2. WisDOT No. 1 limestone coarse aggregate from South Central Wisconsin (Yahara Materials, Madison)

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[1] Granular mixture of sodium hydroxide and calcium hydroxide.  Further details in LaBarca 2006.
[2] Two layers of 4-mil plastic.  Further details in LaBarca 2006.
[3] Material suppliers and manufacturers are listed for completeness and do not imply endorsement or lack of endorsement.  These materials and suppliers were chosen because they represent those materials commonly used in Wisconsin paving operations.

3. WisDOT No. 1 igneous river gravel coarse aggregate from Northwestern Wisconsin (Croell Redi-Mix, LaCrosse)
4. Natural river sand from South Central Wisconsin (Wingra Corp., Madison)
5. Grade 120 slag cement (Lafarge Inc.)
6. Vinsol resin air-entraining agent (SikaLatex)
7. Water-based, wax-based commercial curing compound (W.R. Meadows 1600 white series)
8. AMS-based (alphamethylstyrene-based) commercial curing compound (W.R. Meadows 2200 white series)

The fine and coarse aggregate gradations are provided in Appendix III. Chemical composition and fineness values for the portland cement and slag cement can also be found in Appendix III. The portland cements were randomly assigned a letter from A to D so that the results are anonymous.

All materials were used as provided by the manufacturer except for the coarse and fine aggregates. Aggregates were oven-dried for a minimum of 24 hours and allowed to cool to ambient temperature before use. This additional step was taken to gain maximum control over the aggregate water content. During mix design, the amount of water needed to achieve a w/cm ratio of 0.45 was adjusted by the amount of water absorbed by the aggregates. Adjustments were made according to coarse and fine aggregate absorptions values, which were measured according to ASTM C127 and C128. Aggregate absorption values are provided in Table 5.

According to gradation analyses, both the limestone and igneous coarse aggregates had slightly high large-diameter (greater than one inch) fractions and therefore did not strictly meet Wisconsin Department of Transportation requirements for No. 1 stone (WisDOT 2005). Due to the comparative nature of the project, the perceived minor impact of these variations on the objectives of the research, and project scheduling and time constraints, the coarse aggregate was not re-ordered from the supplier. The fine aggregate complied with Wisconsin Department of Transportation requirements (WisDOT 2005). The aggregates were representative of the materials predominantly used in concrete construction in the northern and southern portions of the state.

**Table 5.** Aggregate Absorption Values

| Aggregate | Absorption Value |
|---|---|
| Limestone (Coarse) | 1.97% |
| Igneous (Coarse) | 1.25% |
| Sand (Fine) | 0.72% |

## 4.3 Mix Design and Specimen Preparation

All mix proportions were based on Wisconsin Department of Transportation Grade A and Grade A-S mix designs (2005). The proportions for each mix design are listed in Table 6. All concrete mixes were prepared with a w/cm ratio of 0.45 and a plastic air content of 6% ± 0.5%. The concrete mixing was conducted by two researchers using a 6-ft$^3$ drum mixer using the procedure specified in ASTM C192. A vinsol resin air-entraining agent from one manufacturer and one shipment was used for all mixing. Plastic air content was measured according to ASTM C231. The coarse aggregate air correction factors were 0.7% and 0.6% for limestone and igneous aggregates, respectively. When the prescribed air content was not achieved, the mix was discarded and performed again on a different date. All specimens were consolidated using a heavy-duty vibration table. Specimens were subsequently placed under wet burlap and covered with plastic for 24 hours before demolding.

Batches for Task 2 yielded specimens for compressive strength cylinders, split-tensile strength cylinders, shrinkage specimens, and hardened air void specimens. Mixes were performed at ambient lab temperatures and also at cold temperatures (40°F). All four cement brands, A, B, C, and D, were used in Task 2 mixes. After demolding, specimens were stored in a 100% humidity room until the appropriate test date.

Batches for Task 3 yielded specimens for deicer scaling resistance test blocks and carbonation test blocks. All Task 3 batches used the same mix designs used in Task 2 and were prepared at ambient lab temperatures. Cements A and C were used in Task 3 mixes. After demolding, specimens were cured according to the curing methods described in Table 4. Three scaling block specimens and one carbonation specimen were cured with each method.

**Table 6.** Mix Proportions (lb/yd$^3$)

| Material | Proportion | | |
|---|---|---|---|
| | 0% Slag Cement | 30% Slag Cement | 50% Slag Cement |
| Coarse Aggregate | 1874 | 1863 | 1858 |
| Fine Aggregate | 1250 | 1242 | 1237 |
| Portland Cement | 564 | 397 | 286 |
| Slag Cement | 0 | 167 | 286 |
| Net Water     w/cm = 0.45 | 254 | 254 | 257 |
| Adjusted Water | | | |
|    Limestone Mixes | 300 | 300 | 302 |
|    Igneous Mixes | 286 | 286 | 289 |

## 4.4 Test Methods

Tests of the hardened concrete were conducted according to the applicable standards listed in Tables 2 and 3.

### 4.4.1 Compression Testing

Compression tests of 4-in diameter by 8-in long concrete cylinders were completed according to ASTM C39. The cylinders were wet cured until testing. Tests were performed at 3, 7, 14, 28, 56, and 365 days. Prior to testing the specimens were capped with a sulfur-based compound in accordance with ASTM C617. Five specimens were tested from each mix at each age, and an average compressive strength at each age was recorded. Compression tests were conducted on a 400,000 pound hydraulic testing machine consistent with ASTM C 39 and ASTM E 4.

Using the equation introduced by Popovics (1998), the compressive strengths were adjusted for the small differences in air content among mixes (Equation 1). This formula is based on the assumption that for every 1% increase in air content, the compressive strength is reduced by 5%.

$$f_{cCorrected} = f_{cMeasured}\left(\frac{1-0.05*6.0\%}{1-0.05*n}\right) \qquad \text{(Equation 1)}$$

where $f_c$ is the compressive strength, and $n$ is the fresh air content, expressed as a percentage.

### 4.4.2 Split-Tensile Testing

Split tension tests were performed at the same ages as the compressive tests. Five cylinders were tested at each age, and an average split-tensile strength was calculated. The tests were conducted according to ASTM C 496. A device for marking diametral lines was constructed to mark the center of the samples. Balsa wood strips with dimensions of 8-in x ¾-in x ⅛-in were used as bearing strips on the top and bottom of the specimens. All cylinders were tested in the moist condition.

### 4.4.3 Air Dried Shrinkage Testing

Determination of length change due to drying shrinkage followed ASTM C157 and ASTM C490. For each mix, three specimens were cast using a 10-in long mold with a 4-in x 4-in cross section. Gage studs for length change measurement were embedded in the concrete. An initial length measurement for each sample was taken after the samples were demolded. Specimens were then cured for 14 days in the 100% humidity room. After 14 days, specimens were stored in an environmental chamber at 50% relative humidity and 73° F. Length measurements were taken for each sample every day from 14 to 21 days, every three days from 21 to 56 days, and every seven days from 56 to 120 days. Equation 2 was used to determine the length change percentage at each time

period.  Results from the three specimens for each mix were averaged to establish the shrinkage associated with a mix.

$$\Delta L_x = \frac{L_x - L_i}{100G}$$  (Equation 2)

where $\Delta L_x$ equals the length change at age x, $L_x$ equals the comparator reading at age x, $L_i$ equals the initial comparator reading of the specimen, and $G$ represents the gage length of the reference bar (10 in).

### 4.4.4  Hardened Air Void Analysis

The hardened air void analyses were performed by American Petrographic Services (APS), Inc. of St. Paul, Minnesota, following the procedures of ASTM C 457.  Samples were taken from the middle of 3-in x 4-in x 16-in prisms and sent to APS.  Specimens sent for air void analyses were selected from the same batches used for compressive strength testing.  The results of the hardened air void analyses were compared to the fresh air contents of the mix and any abnormalities in the air void distribution were noted.

### 4.4.5  Deicer Scaling Testing

Deicer scaling tests were performed according to a modified ASTM C672 procedure.  Just before freeze-thaw testing began (at an age of 28 days), a water-tight dam was constructed around the perimeter of the scaling blocks using a layer of insulating foam[4] that expanded upon application to a height and width of one inch.  To insure a water-tight seal, a line of caulk[5] was applied around the inside and outside of the foam dam where the dam adhered to the concrete.  For specimens tested with soda lime and plastic wrap, the soda lime pellets and plastic were removed before application of the dam.

After the 28-day curing period, scaling block specimens complete with water-tight dams were placed in a freeze-thaw room located at the UW – Madison Biotron.  The room had capacity to simultaneously expose 96 scaling blocks to the freeze-thaw temperature regime.  Each complete freeze-thaw cycle lasted for one day.  During the freeze portion of the cycle, a temperature of negative 62°F plus or minus 3°F was maintained in the freeze-thaw room for 18 hours.  For the remaining 6 hours of the cycle, the concrete was thawed at a temperature of 85°F.  A ¼-inch deep 4% sodium chloride solution was maintained on the surface of the specimens for the duration of the freeze-thaw cycling.  ASTM C672 recommends a 4% calcium chloride solution but allows for different chemical solutions where appropriate.  Sodium chloride is the particular deicer salt applied to roadways in the state of Wisconsin.  Additionally, previous research has shown that specimens tested with a calcium chloride salt solution experienced very little scaling (Ballweg, 2002).  For these two reasons, use of a sodium chloride solution was practical for this study.

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[4] "Great Stuff Pro" window and door insulating foam sealant (polyurethane), manufactured by Dow Chemical Company.
[5] "Painter's Preferred" acrylic latex caulk, manufactured by White Lightning Products.

The freeze-thaw testing for a specimen was complete after 60 freeze-thaw cycles. ASTM C672 recommends testing with at least 50 freeze-thaw cycles, unless clear scaling patterns have not been noted by that point. In Phase I of this project, specimens were tested for a total of 100 cycles. However, it was determined from Phase I data that most of the significant deicer scaling had occurred by 50 or 60 cycles. Therefore, 60 freeze-thaw cycles were executed for this portion of the project. Reducing the number of cycles from 100 to 60 allowed for testing of more specimens over a shorter period of time and eliminated redundant testing after a specimen's scaling rate had decreased. If a specimen still exhibited large amounts of scaling at 60 cycles, however, cycling was continued for that particular specimen until its scaling rate decreased sufficiently.

The deicer scaling loss test was performed in the following manner. After every five freeze-thaw cycles, specimens were removed from the freeze-thaw chamber during a thaw period. The exposed surface of each specimen was rinsed in a repeatable manner, and scaling material was collected in a number 200 (75μm opening) sieve. The scaling material was subsequently dried and weighed in a glass mason jar, and the weight was recorded. Immediately after surface rinsing, the specimen was returned to the freeze-thaw chamber, and the salt solution was reapplied.

The deicer scaling loss test used in this study differs from the test prescribed by ASTM C672. The standard does not require collection and weighing of the scaling loss material. Instead, a visual rating system is to be implemented after every five freeze-thaw cycles, based on the guidelines shown in Table 7. The visual rating test was also carried out in this study, and data for that test is provided in the Appendix VII.

**Table 7.** ASTM C672 Visual Rating System Guidelines

| Rating | Surface Condition |
|--------|-------------------|
| 0 | No Scaling |
| 1 | Very light scaling (3mm depth max; no coarse agg. visible) |
| 2 | Slight to moderate scaling |
| 3 | Moderate scaling (some coarse agg. visible) |
| 4 | Moderate to severe scaling |
| 5 | Severe scaling (coarse agg. visible over entire surface) |

*4.4.6 Carbonation Testing*

Carbonation tests were performed based on the RILEM CPC18 standard. Carbonation tests were performed at concrete ages of 14, 28, 40, 60, and 80 days. Carbonation testing blocks (16-in x 3-in x 4-in) were cured using the same methods described in Table 4. After the 28-day curing period, carbonation blocks remained in laboratory conditions.

Soda lime pellets and plastic wrap were removed from carbonation blocks at 28 days, and curing compounds (if used) remained on the carbonation blocks.

During a carbonation test, the carbonation testing blocks were cut so that a fresh surface was exposed for testing. A concrete masonry saw was used to cut a two-inch piece off of the end of each 16-inch long carbonation testing block. The resulting 3-in x 4-in fresh surface was sprayed with a phenolphthalein pH indicator. The indicator turned pink on the portion of the concrete surface that was not carbonated. The carbonated area remained colorless. The depth of the colorless (carbonated) area of the concrete was measured using an optical glass magnifier scale. Measurements were taken to the nearest 0.1mm. If the depth varied across the 4-inch section, the several or more depths were measured, and an average was computed.

## 5. Test Results and Comparison to Grade 100 Slag Cement

## 5.1 Slag Cement Variability

A portion of this study was devoted to the investigation of slag cement uniformity from a local supplier. The supplier, located in South Central Wisconsin, provided monthly Grade 120 slag cement samples from its concrete mixing plant. Each sample represented a different slag cement shipment to the supplier, and therefore the uniformity of material received by the supplier could be tested. The supplier's slag cement was of the same grade and brand used for concrete mixes in this study. A total of twelve monthly samples were received and analyzed from October, 2004 through September, 2005. Each monthly sample was tested for chemical composition (ASTM C114), fineness (ASTM C204), and hydraulic activity with OPC (ASTM C989).

### 5.1.1 Blaine Fineness

Blaine fineness tests for all monthly slag cement samples and for the research slag were conducted at a commercial laboratory. Test results are given in $m^2$/kg and indicate the specific surface area of a unit weight of material (Table 8). The variation in Blaine fineness among monthly samples is not large – the coefficient of variation is just under 3%. The Blaine fineness for the research slag cement used to make specimens for this study was 508 $m^2$/kg, which places the research sample in the less fine range of the monthly samples.

**Table 8.** Blaine Fineness Values for Monthly Slag Cement Samples

| Sample | Blaine Fineness $m^2$/kg | Sample | Blaine Fineness $m^2$/kg |
|---|---|---|---|
| October | 519 | April | 531 |
| November | 508 | May | 535 |
| December | 508 | June | 519 |
| January | 555 | July | 526 |
| February | 527 | August | 521 |
| March | 527 | September | 557 |
| Average | | 528 $m^2$/kg | |
| Standard Deviation | | 15.5 $m^2$/kg | |
| Coefficient of Variation | | 2.9% | |

*5.1.2 Chemical Composition*

Chemical analyses for all monthly slag cement samples and for the research slag were conducted at a commercial laboratory. Chemical constituents are reported as a function of their oxides (Table 9). Over the given 12-month period, chemical composition of the local supplier's slag cement shipments exhibited only slight variation. Composition of each monthly sample was also similar to that of the slag cement used for concrete mixes in this study. However, the small differences in composition from month to month could affect the hydraulic activity of the slag cement. This influence is reported in Section 5.1.4.

**Table 9.** Chemical Composition of Monthly Slag Cement Samples, percent

| | $SiO_2$ | $Al_2O_3$ | $TiO_2$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $Mn_2O_3$ | SrO | $SO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Oct** | 35.52 | 10.48 | 0.57 | 0.43 | 39.17 | 11.54 | 0.18 | 0.34 | 0.44 | 0.04 | 2.56 |
| **Nov** | 35.55 | 10.22 | 0.56 | 0.43 | 38.76 | 11.37 | 0.18 | 0.34 | 0.38 | 0.04 | 2.46 |
| **Dec** | 35.03 | 10.09 | 0.60 | 0.61 | 39.00 | 10.45 | 0.20 | 0.30 | 0.54 | 0.04 | 2.47 |
| **Jan** | 35.51 | 9.93 | 0.56 | 0.45 | 39.33 | 11.17 | 0.20 | 0.41 | 0.50 | 0.04 | 2.68 |
| **Feb** | 33.63 | 9.71 | 0.64 | 0.50 | 38.57 | 11.04 | 0.29 | 0.31 | 0.50 | 0.04 | 2.85 |
| **Mar** | 34.83 | 10.80 | 0.54 | 0.85 | 40.01 | 11.23 | 0.28 | 0.25 | 0.28 | 0.04 | 2.79 |
| **Apr** | 35.21 | 10.58 | 0.55 | 0.53 | 40.13 | 10.90 | 0.23 | 0.23 | 0.30 | 0.04 | 2.62 |
| **May** | 35.61 | 10.30 | 0.51 | 0.56 | 40.18 | 10.96 | 0.26 | 0.26 | 0.26 | 0.04 | 2.61 |
| **Jun** | 35.16 | 10.76 | 0.59 | 0.41 | 38.92 | 11.63 | 0.25 | 0.29 | 0.34 | 0.04 | 2.57 |
| **Jul** | 34.71 | 10.14 | 0.55 | 0.57 | 39.49 | 11.09 | 0.24 | 0.27 | 0.33 | 0.04 | 2.63 |
| **Aug** | 36.41 | 10.88 | 0.63 | 0.33 | 38.32 | 11.87 | 0.27 | 0.26 | 0.44 | 0.04 | 2.63 |
| **Sep** | 35.87 | 11.00 | 0.65 | 0.45 | 38.53 | 11.93 | 0.27 | 0.36 | 0.62 | 0.04 | 2.45 |
| **Research Slag Cement** | 35.12 | 10.06 | 0.30 | 0.30 | 39.89 | 11.00 | 0.18 | 0.30 | 0.20 | 0.04 | 2.63 |

*5.1.3 Slag Activity Index*

The slag activity index was measured in-house for all monthly slag cement samples and for the research slag cement. This test involves a comparison of the 7-day and 28-day compressive strengths of 50% slag cement/50% OPC mortar to the strength of 100% OPC mortar at the same ages. The slag activity index (SAI) is given as

$$SAI = \frac{f_{slag\,cement}}{f_{OPC}} x100 \qquad \text{(Equation 3)}$$

where $f_{slag\,cement}$ is the compressive strength of the mortar made with 50% slag cement in psi, and $f_{OPC}$ is the compressive strength of 100% OPC mortar in psi. The reference cement in all cases was Cement C. Results of the slag activity tests are provided in Figure 1, and statistical information is provided in Table 10. In Figure 1, the 7-day and 28-day requirement levels represent the ASTM C989 minimum SAI for a given slag cement to be considered Grade 120. At the 7-day test age, 9 of the 12 monthly slag cement samples passed the 95% SAI requirement. At 28 days, 11 of the 12 samples passed the 115% SAI requirement. The statistics reported in Table 10 indicate slight variability among the monthly samples; however, a coefficient of variation less than 10% is regarded as acceptable. Additionally, variability of this magnitude can be expected with use of slag cement.[6]

The slag activity index test was also performed with the research slag cement and the four brands of OPC used in this study. In all cases, the minimum ASTM C989 requirement was met for Grade 120 slag cement (Figure 2).

**Table 10.** Statistical Information for
Slag Activity Index Test Results

| Test Age | Average | Standard Deviation | Coefficient of Variation |
|----------|---------|--------------------|--------------------------|
| 7 Days | 95% | 8.8% | 9.3% |
| 28 Days | 123% | 9.8% | 8.0% |

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[6] Based on personal conversation with a technical sales engineer representing a slag cement manufacturer.
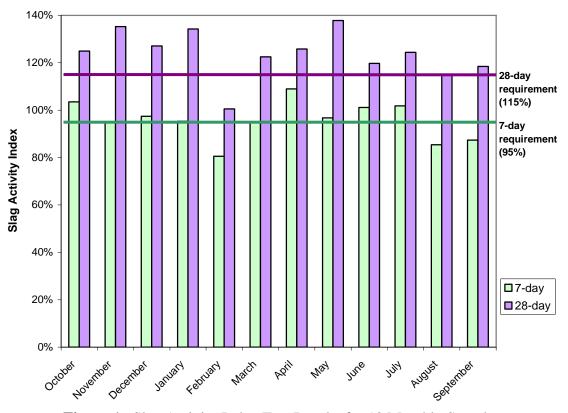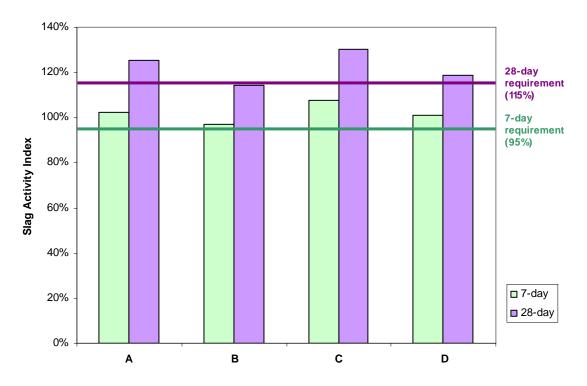
**Figure 1.** Slag Activity Index Test Results for 12 Monthly Samples



**Figure 2.** Slag Activity Index Test Results for
Research Slag Cement and Four Ordinary Portland Cements

## 5.1.4  Correlation Between Fineness, Chemistry, and Slag Activity

Although the variability of slag activity among the twelve monthly samples can be considered typical, the underlying cause of the variation among the 12 monthly samples was investigated.  It was expected that changes in fineness, chemistry, or both would impact the SAI values obtained.  Linear and quadratic regression analyses were performed to determine if a correlation existed between slag activity and these two parameters.

For both the linear fit and the quadratic fit, there was effectively no correlation between the Blaine fineness value and the SAI.  However, a correlation was noted between the 7- and 28-day SAI and several of the major chemical components of slag cement.  These components and the $R^2$ value for their respective regression analyses are provided in Table 11.

The $SiO_2$, $Al_2O_3$, and CaO components together comprise over 85% of the total slag cement composition.  Therefore, these oxides are significant in the slag cement hydration process.  It can be concluded from the SAI correlation that even the small composition changes of these oxides noted among the 12 monthly slag cement samples result in changes in slag activity and thus strength of slag cement mortars.

Also noteworthy is that the SAI correlation with CaO is high at 7 days and lower at 28 days.  This implies that the influence of lime content on slag cement hydration is initially strong, and its influence decreases as the mortar ages.  As discussed in Chapter 2, a small amount of slag cement hydration takes place immediately after contact with water.  It has also been noted that the product of this initial hydration is C-S-H, whose base component is derived from the CaO in the slag cement (Regourd, et al., 1983).  Therefore, initial slag cement hydration and thus initial strength gain is dependent on lime content, as reflected in the correlation with the SAI at 7 days.

**Table 11.**  Parameters with Possible Correlation to Slag Activity Index

| Parameter | $R^2$ Value, Quadratic Fit | |
| --- | --- | --- |
| | 7-days | 28-days |
| $SiO_2$ | 0.69 | 0.70 |
| $Al_2O_3$ | 0.70 | 0.61 |
| CaO | 0.62 | 0.36 |
| $TiO_2$ | 0.66 | 0.59 |
| $Na_2O$ | 0.59 | 0.51 |

## 5.2  Plastic Concrete Testing

Three fresh concrete tests were performed just after the concrete was removed from the mixer:  slump, unit weight, and fresh air content.  In addition, hardened air void analyses were performed at a commercial laboratory for concrete taken from the batch mixed for compression testing.  The results of these tests for batches assigned to strength-testing concrete specimens are provided for ambient and cold conditions in Tables 12 and 13, respectively.  Fresh concrete test results for batches assigned to deicer scaling concrete specimens are provided in Table 14.

Slump values for concrete mixed at ambient conditions ranged from 1.0 to 5.25 inches.  The type of coarse aggregate used affected the slump:  concrete made with igneous coarse aggregate generally had higher slump values than did limestone concrete.  This difference is likely due to the smooth surfaces and rounded nature of the igneous aggregate compared to the rough surfaces and more angular shape of the limestone aggregate.  It is also evident that slump varied with cement brand; this is possibly a result of differences in cement fineness.  The level of slag cement replacement, however, did not have a significant effect on slump.  Slump for concrete mixed at 40°F was slightly lower than for concrete mixed in ambient conditions.

The target fresh air content was 6%, and air content values between 5.5% and 6.5% were accepted.  Concrete that did not fall within this range for air content was rejected, and that particular batch was remixed.  Therefore, all concrete mixes used to prepare test specimens were ultimately within the acceptable range.  The amount of air entraining admixture (AEA) necessary to obtain 6%±0.5% fresh air content was not consistent among all mixes.  In general, the amount of AEA necessary increased as the level of slag cement replacement increased.  This phenomenon was likely because slag cement is a finer material than OPC.  Cement brand and the type of coarse aggregate also affected the amount of AEA required.  Concrete mixed at 40°F required slightly less AEA to obtain 6%±0.5% fresh air content.

Hardened air void content did not match the measured fresh air content in most cases.  The average fresh air content for all concrete mixed at ambient conditions was 6.0%, but the average hardened air content was 5.5%.  Most of the individual hardened air content values were less than the corresponding fresh air content values, which suggests that a small amount of entrapped air may have influenced the fresh concrete measurements.  This phenomenon may also be attributed to loss of air during placement and consolidation of the air void specimens.  Similar results were noted for 40°F concrete.  A summary of the hardened air void analysis for each specimen is included in Appendix IV.

According to ACI Committee 212.3R (2004), cement paste consistent with good freeze thaw durability will have a spacing factor less than 0.008 inches, a specific surface greater than 600 $in^2/in^3$, and the number of air voids per inch significantly greater than the percentage of air in the concrete.  All concrete tested in this study, including 40°F mixes, exhibited the above characteristics (Appendix IV).  Spacing factors ranged from 0.003 to 0.006 inches, and the specific surface values ranged from 790 to 1420 $in^2/in^3$.

**Table 12.** Fresh Concrete Properties – Strength-Testing Concrete; Ambient Conditions

| Coarse Aggregate | Cement | Slag Cement Replacement | Batch ID | Slump (in) | Unit Weight (lb/ft$^3$) | Fresh Air Content (%) | Hardened Air Content (%) |
|---|---|---|---|---|---|---|---|
| Limestone | A | 0% | 4-C | 1.75 | 146.6 | 5.5 | 5.2 |
| | | | 4-T | 1.75 | 145.7 | 5.9 | |
| | | 30% | 5-C | 2.00 | 145.3 | 6.3 | 5.9 |
| | | | 5-T | 2.50 | 144.5 | 6.2 | |
| | | 50% | 6-C | 2.25 | 144.7 | 5.7 | 3.8 |
| | | | 6-T | 2.50 | 144.7 | 5.8 | |
| | B | 0% | 19-C | 1.75 | 146.4 | 5.5 | 5.3 |
| | | | 19-T | 1.00 | 147.2 | 5.7 | |
| | | 30% | 20-C | 2.75 | 144.4 | 6.5 | 4.2 |
| | | | 20-T | 2.75 | 145.6 | 6.3 | |
| | | 50% | 21-C | 2.25 | 145.7 | 5.6 | 4.1 |
| | | | 21-T | 2.50 | 144.5 | 6.3 | |
| | C | 0% | 7-C | 3.50 | 145.6 | 5.5 | 3.5 |
| | | | 7-T | 3.50 | 144.1 | 5.7 | |
| | | 30% | 8-C | 2.75 | 144.8 | 5.6 | 4.4 |
| | | | 8-T | 2.75 | 145.6 | 5.6 | |
| | | 50% | 9-C | 3.00 | 143.6 | 5.9 | 4.5 |
| | | | 9-T | 2.00 | 145.2 | 5.5 | |
| | D | 0% | 1-C | 2.75 | 145.3 | 6.1 | 6.3 |
| | | | 1-T | 2.25 | 145.7 | 5.7 | |
| | | 30% | 2-C | 2.00 | 144.8 | 6.1 | 4.5 |
| | | | 2-T | 2.50 | 143.9 | 6.3 | |
| | | 50% | 3-C | 2.25 | 144.5 | 5.7 | 4 |
| | | | 3-T | 2.50 | 144.5 | 5.9 | |
| Igneous | A | 0% | 13-C | 2.50 | 144.4 | 6.5 | 5.9 |
| | | | 13-T | 4.00 | 146.0 | 5.9 | |
| | | 30% | 14-C | 3.75 | 145.6 | 6.1 | 4.9 |
| | | | 14-T | 3.50 | 146.0 | 5.8 | |
| | | 50% | 15-C | 3.25 | 146.4 | 5.7 | 4.6 |
| | | | 15-T | 3.00 | 145.6 | 5.8 | |
| | B | 0% | 22-C | 3.00 | 147.6 | 6 | 5.8 |
| | | | 22-T | 3.25 | 147.2 | 6.4 | |
| | | 30% | 23-C | 3.50 | 146.4 | 6.1 | 5.7 |
| | | | 23-T | 3.75 | 147.2 | 5.8 | |
| | | 50% | 24-C | 3.50 | 146.8 | 5.7 | 4.7 |
| | | | 24-T | 3.50 | 146.4 | 5.9 | |
| | C | 0% | 16-C | 4.25 | 146.0 | 6.5 | 6.4 |
| | | | 16-T | 4.75 | 146.0 | 6.1 | |
| | | 30% | 17-C | 4.00 | 147.6 | 5.5 | 4.5 |
| | | | 17-T | 4.00 | 147.2 | 5.5 | |
| | | 50% | 18-C | 4.25 | 146.0 | 6.1 | 5.8 |
| | | | 18-T | 3.50 | 145.6 | 6.3 | |
| | D | 0% | 10-C | 4.50 | 145.2 | 6.4 | 7.5 |
| | | | 10-T | 4.50 | 144.4 | 6.5 | |
| | | 30% | 11-C | 4.00 | 144.8 | 6.5 | 6.7 |
| | | | 11-T | 4.00 | 144.8 | 6.5 | |
| | | 50% | 12-C | 4.50 | 145.2 | 6.3 | 5.9 |
| | | | 12-T | 4.50 | 146.0 | 6.3 | |

**Table 13.** Fresh Concrete Properties – Strength-Testing Concrete; 40°F Conditions

| Coarse Aggregate | Cement | Slag Cement Replacement | Batch ID | Slump (in) | Unit Weight (lb/ft$^3$) | Fresh Air Content (%) | Hardened Air Content (%) |
|---|---|---|---|---|---|---|---|
| Limestone | D (40°F) | 0% | 25-C | 1.50 | - | 5.5 | 5.6 |
| | | | 25-T | 2.00 | 148.4 | 5.6 | |
| | | 30% | 26-C | 2.00 | 139.6 | 7 | 6.6 |
| | | | 26-T | 1.75 | 140.8 | 5 | |
| | | 50% | 27-C | 1.75 | 142.8 | 5.5 | 5.2 |
| | | | 27-T | 1.75 | 141.6 | 5.7 | |
| Igneous | D (40°F) | 0% | 28-C | 4.00 | 146.0 | 6.9 | 7.6 |
| | | | 28-T | 3.50 | 147.6 | 6 | |
| | | 30% | 29-C | 3.00 | 146.4 | 6.2 | 6 |
| | | | 29-T | 3.00 | 147.6 | 5.7 | |
| | | 50% | 30-C | 2.75 | 146.8 | 6 | 8.9 |
| | | | 30-T | 3.25 | - | 5.8 | |

**Table 14.** Fresh Concrete Properties – Deicer Scaling Test Concrete

| Coarse Aggregate | Cement | Slag Cement Replacement | Batch ID | Slump (in) | Unit Weight (lb/ft$^3$) | Fresh Air Content (%) |
|---|---|---|---|---|---|---|
| Limestone | A | 0% | 1-a | 1.75 | 144.9 | 5.9% |
| | | | 1-b | 1.5 | 144.9 | 6.0% |
| | | 30% | 2-a | 1.75 | 144.5 | 5.9% |
| | | | 2-b | 1.25 | 145.3 | 5.6% |
| | | | 2-c | 1.25 | 146.9 | 5.7% |
| | | 50% | 3-a | 1.5 | 145.7 | 5.5% |
| | | | 3-b | 1.75 | 143.7 | 5.7% |
| | | | 3-c | 2 | 143.3 | 6.3% |
| | C | 0% | 4-a | 2 | 146.1 | 5.7% |
| | | | 4-b | 2.5 | 146.1 | 5.6% |
| | | 30% | 5-a | 2.75 | 143.7 | 6.5% |
| | | | 5-b | 2.5 | 144.1 | 6.3% |
| | | | 5-c | 2.5 | 144.1 | 6.1% |
| | | 50% | 6-a | 2.25 | 144.3 | 5.8% |
| | | | 6-b | 2.5 | 144.2 | 5.8% |
| | | | 6-c | 2.5 | 143.7 | 6.2% |
| Igneous | A | 0% | 7-a | 3.75 | 146.1 | 6.3% |
| | | | 7-b | 3.5 | 147.7 | 6.0% |
| | | 30% | 8-a | 3.5 | 146.9 | 6.0% |
| | | | 8-b | 3.5 | 146.1 | 6.0% |
| | | | 8-c | 3.25 | 146.1 | 6.0% |
| | | 50% | 9-a | 4 | 145.3 | 6.3% |
| | | | 9-b | 3.75 | 146.1 | 5.6% |
| | | | 9-c | 3.75 | 146.5 | 5.8% |
| | C | 0% | 10-a | 4.5 | 146.7 | 6.4% |
| | | | 10-b | 4 | 148.1 | 5.7% |
| | | | 10-c | 4.5 | 146.9 | 6.5% |
| | | 30% | 11-a | 5 | 146.5 | 6.4% |
| | | | 11-b | 4.75 | 146.9 | 6.0% |
| | | | 11-c | 5 | 145.7 | 6.5% |
| | | 50% | 12-a | 4.75 | 146.5 | 5.7% |
| | | | 12-b | 4.75 | 147.3 | 5.5% |
| | | | 12-c | 5.25 | 146.1 | 6.1% |

## 5.3 Compression Test Results

The compression test results revealed that the type of coarse aggregate, slag cement replacement level, and portland cement source were all variables which influence concrete compressive strength, but each variable differed in its significance to the overall strength. Concrete made with limestone aggregate was stronger than concrete made with igneous aggregate. The improved strength of limestone aggregate concrete can be seen in the compressive strength versus time plots in Figures 3 through 6 at the end of this section. Based on the average compressive strength of all four portland cement sources for all ages and slag cement replacement levels, limestone aggregate concrete was 11% to 25% stronger than corresponding igneous aggregate concrete for the same mix design.

The improved concrete strength with limestone aggregate was likely due to the rough surface and angularity of the limestone aggregates which improves mechanical interlock at the cement paste-aggregate interface.  There is also some evidence that the limestone aggregates may provide better bonding due to chemical reactions occurring in the interfacial zone (Ezeldin and Aitcin 1991).

The amount of slag cement replacement also had a significant effect on compressive strength.  Slag cement concrete had low early strengths compared to OPC concrete (Figures 3-6).  The low early strengths were expected based on to the fact that slag cement is a latent hydraulic material.  On a log plot of strength versus time, slag cement concrete followed a quadratic relationship while OPC concrete followed a linear relationship.  The difference in the strength gain relationships between OPC concrete and slag cement concrete was due to the fact that slag cement concrete had low strength at early ages, but had increased rates of strength gain beyond 3 days compared to OPC concrete.  Slag cement concrete strength as a percentage of OPC concrete strength at the six test ages is given in Table 15.  Slag cement concrete generally achieved strengths similar to corresponding OPC concrete by 14 days.  After 14 days, slag cement concrete generally met or exceeded the strength of OPC concrete.  At 365 days, the strength of slag cement concrete was on average 104% of the strength of corresponding OPC concrete for limestone coarse aggregate, and 99% of OPC concrete strength for igneous coarse aggregate (Table 15).

The portland cement source had an effect on the compressive strength due to slight differences in the chemistry and fineness of the portland cements.  The difference in strength due to portland cement source decreased with concrete age.  Table 16 shows the difference in compressive strength between the portland cement sources with the lowest strength to the highest strength.  Figures 7 and 8 show the differences in strength between portland cement sources at 0% slag cement replacement for limestone and igneous aggregates respectively.  At an age of 3 days, the maximum percentage difference between the lowest and highest compressive strengths ranged from 17% to 34%.  This was mainly due to the fact that Cement B provided high early strengths which were likely due to its high fineness.  By 28 days, the maximum percentage difference between brands was 10%, and by 365 days it was 15%.  Noticeable differences, especially in early strength, were observed with different cement sources, slag cement replacement levels, and coarse aggregate combinations.

Mixing and curing the concrete at 40°F slowed strength gain significantly for slag cement concrete.  These mixes obtained only about half the strength at 3 days than they would under  normal temperatures.  Compressive strength of the 40°F concrete as a percentage of ambient temperature concrete strength is given in Table 17.  The cold temperature concrete gained strength slowly at early ages regardless of slag cement replacement level.  The OPC 40°F concrete had strengths similar to ambient temperature concrete by 14 days.  Slag cement concrete at 40°F gained strength more slowly compared to the ambient temperature mixes at nearly all ages, and 50% slag cement concrete was most affected.  For both aggregate types, the 56-day strength of 50% slag cement concrete mixed and cured at 40°F was 88% of the strength of ambient temperature concrete.

The Wisconsin DOT requires that concrete reach 3000 psi before it can be opened to traffic (DOT 2005).  The amount of time required for each concrete mix to reach 3000 psi compressive strength under laboratory conditions is provided in Table 18.  Naturally, field conditions could lengthen or shorten these times.  OPC concretes reached 3000 psi in three to four days.  This amount of time is consistent with the equivalent curing time of four days allowed for grade A concrete in provision 415.3.17.1 of the DOT Standard Specifications.  For grade A-S mixtures, the DOT equivalent curing time is seven days.  Concrete made with 30% slag cement replacement reached 3000 psi in three to eight days.  Concrete made with 50% slag cement reached 3000 psi in five to nine days, which in some cases slightly exceeds the seven-day equivalent curing requirement.  It is important to note that this study used a w/cm ratio of 0.45.

At 40°F, the Wisconsin DOT provision 415.3.17.1 uses 0.6 equivalent curing days per calendar day to adjust for the slowed strength gain in cold temperatures.  Under this standard, OPC concrete at 40°F must achieve 3000 psi in seven days.  Slag cement concrete has 12 days to reach 3000 psi.  In this study, OPC concrete and 30% slag cement concrete at 40°F met the DOT equivalent curing time requirements (Table 18).  However, the 50% slag cement concrete at 40°F did not achieve 3000 psi until ages of 16 and 18 days for limestone and igneous aggregate concretes respectively, which exceeds the WisDOT curing time requirements.

**Table 15.** Slag Cement Concrete Strength as a Percentage of OPC Concrete Strength

| Cement | Aggregate | % Slag | 3-day | 7-day | 14-day | 28-day | 56-day | 365-day |
|--------|-----------|--------|-------|-------|--------|--------|--------|---------|
| **A** | **Limestone** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 80% | 89% | 101% | 107% | 115% | 107% |
| | | **50%** | 60% | 76% | 93% | 103% | 112% | 97% |
| | **Igneous** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 77% | 87% | 100% | 105% | 105% | 98% |
| | | **50%** | 66% | 83% | 95% | 97% | 102% | 96% |
| **B** | **Limestone** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 89% | 96% | 104% | 103% | 109% | 108% |
| | | **50%** | 65% | 86% | 102% | 107% | 110% | 103% |
| | **Igneous** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 89% | 93% | 91% | 101% | 101% | 97% |
| | | **50%** | 72% | 87% | 92% | 98% | 102% | 98% |
| **C** | **Limestone** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 86% | 98% | 101% | 108% | 111% | 104% |
| | | **50%** | 63% | 87% | 100% | 100% | 108% | 101% |
| | **Igneous** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 79% | 98% | 99% | 107% | 108% | 104% |
| | | **50%** | 70% | 91% | 96% | 101% | 101% | 99% |
| **D** | **Limestone** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 84% | 93% | 100% | 108% | 106% | 107% |
| | | **50%** | 69% | 83% | 99% | 98% | 104% | 104% |
| | **Igneous** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 77% | 96% | 97% | 101% | 95% | 95% |
| | | **50%** | 68% | 85% | 98% | 104% | 104% | 102% |
| **Average** | **Limestone** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 85% | 94% | 102% | 106% | 110% | 106% |
| | | **50%** | 64% | 83% | 98% | 102% | 108% | 101% |
| | **Igneous** | **0%** | 100% | 100% | 100% | 100% | 100% | 100% |
| | | **30%** | 81% | 93% | 97% | 103% | 102% | 98% |
| | | **50%** | 69% | 87% | 95% | 100% | 102% | 99% |

**Table 16.** Percentage Difference Between Lowest to the Highest Compressive Strength
Based on Different Portland Cement Sources

| Coarse Aggregate | Slag Cement Replacement | Age (Days) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 3 | 7 | 14 | 28 | 56 | 365 |
| Limestone | 0% | 17% | 13% | 8% | 8% | 14% | 12% |
| | 30% | 21% | 11% | 9% | 9% | 13% | 15% |
| | 50% | 19% | 17% | 9% | 10% | 12% | 9% |
| Igneous | 0% | 17% | 14% | 15% | 7% | 5% | 8% |
| | 30% | 34% | 21% | 5% | 6% | 9% | 4% |
| | 50% | 28% | 18% | 11% | 9% | 9% | 9% |

**Table 17.** Compressive Strength of 40°F Concrete
as a Percentage of Ambient Temperature Concrete Strength
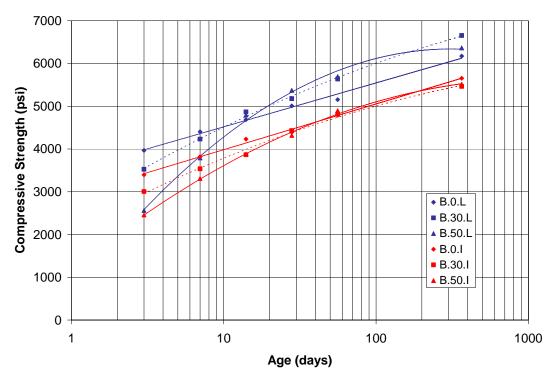
| Coarse Aggregate | Slag Cement Replacement | Age (Days) | | | | |
|---|---|---|---|---|---|---|
| | | 3 | 7 | 14 | 28 | 56 |
| Limestone | 0% | 49% | 76% | 100% | 108% | 106% |
| | 30% | 42% | 61% | 75% | 80% | 94% |
| | 50% | 31% | 46% | 60% | 82% | 88% |
| Igneous | 0% | 62% | 91% | 104% | 111% | 102% |
| | 30% | 55% | 72% | 88% | 95% | 105% |
| | 50% | 36% | 78% | 72% | 86% | 88% |

**Table 18:** Time Required to Reach
Opening Traffic Strength of 3000 psi

| Cement | Aggregate | Slag Replacement | Days to Reach 3000 psi |
|---|---|---|---|
| A | Limestone | 0% | 3 |
| | | 30% | 4 |
| | | 50% | 7 |
| | Igneous | 0% | 4 |
| | | 30% | 8 |
| | | 50% | 9 |
| B | Limestone | 0% | 3 |
| | | 30% | 3 |
| | | 50% | 5 |
| | Igneous | 0% | 3 |
| | | 30% | 3 |
| | | 50% | 6 |
| C | Limestone | 0% | 3 |
| | | 30% | 4 |
| | | 50% | 6 |
| | Igneous | 0% | 4 |
| | | 30% | 6 |
| | | 50% | 7 |
| D | Limestone | 0% | 3 |
| | | 30% | 3 |
| | | 50% | 5 |
| | Igneous | 0% | 4 |
| | | 30% | 7 |
| | | 50% | 8 |
| D - 40° F | Limestone | 0% | 7 |
| | | 30% | 11 |
| | | 50% | 16 |
| | Igneous | 0% | 7 |
| | | 30% | 12 |
| | | 50% | 18 |
| Average (Ambient) | Limestone | 0% | 3 |
| | | 30% | 4 |
| | | 50% | 6 |
| | Igneous | 0% | 4 |
| | | 30% | 6 |
| | | 50% | 8 |
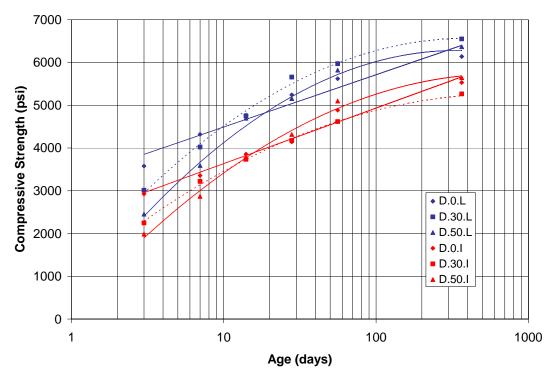
**Figure 3.** Compressive Strength Trends for Cement A Concrete
(Key: cement source, slag cement %, aggregate type: L = limestone, I = igneous)



**Figure 4.** Compressive Strength Trends for Cement B Concrete
(Key: cement source, slag cement %, aggregate type: L = limestone, I = igneous)

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**Figure 5.** Compressive Strength Trends for Cement C Concrete
(Key: cement source, slag cement %, aggregate type: L = limestone, I = igneous)



**Figure 6.** Compressive Strength Trends for Cement D Concrete
(Key: cement source, slag cement %, aggregate type: L = limestone, I = igneous)
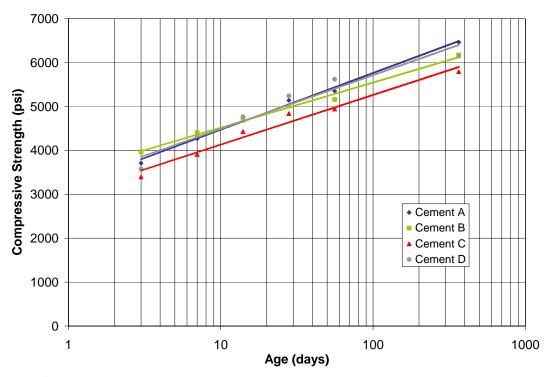
**Figure 7.** Compressive Strength Trends for Four Sources of Portland Cement
and Limestone Coarse Aggregate; 0% Slag Cement Replacement
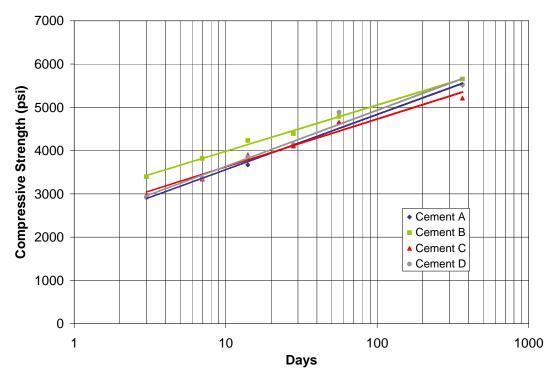


**Figure 8.** Compressive Strength Trends for Four Sources of Portland Cement
and Igneous Coarse Aggregate; 0% Slag Cement Replacement

26
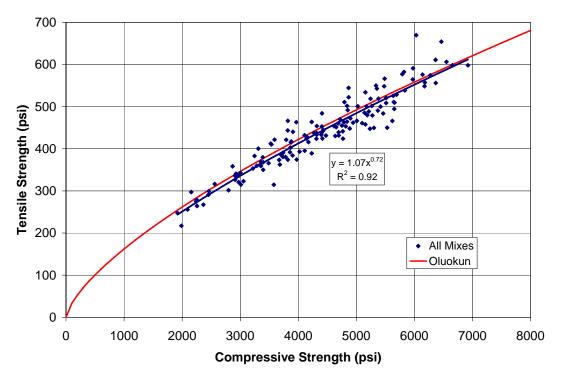
## 5.4 Split Cylinder Tensile-Compressive Strength Relationship

Concrete tested in this study closely followed the split cylinder tensile-compressive strength relationship developed by Oluokun (1991):
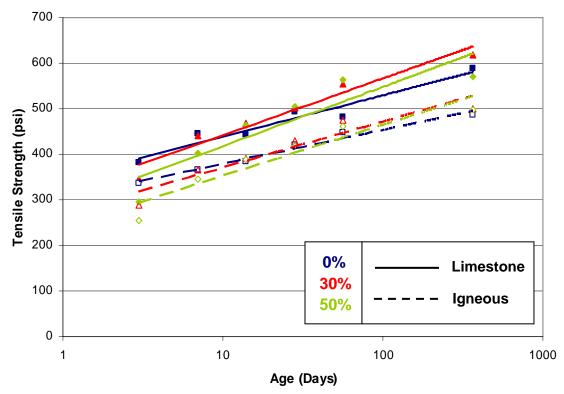
$$f_t = 1.38 f_c^{0.69}$$

<div align="right">(Equation 4)</div>

where the split-cylinder tensile strength, $f_t$, and the compressive strength, $f_c$, are in psi. The Oluokun relationship is based on a number of studies of concrete with a variety of mix constituents. The tensile-compressive strength relationship for ambient temperature concrete compared to the Oluokun relationship is demonstrated in Figure 9. Split-cylinder tensile strength data for each mix are given in Appendix VI. The tensile-compressive strength data in this study agreed well with the Oluokun relationship (Figure 9).

Many trends regarding material variations were similar for tensile strength and compressive strength. Split-cylinder tensile strength values averaged over cement source are plotted with time in Figure 10. The type of coarse aggregate used had a significant effect: use of limestone coarse aggregate yielded concrete with higher split-tensile strength values than did igneous coarse aggregate (Figure 10). The effect of slag cement replacement level on tensile strength is also similar to the effect on compressive strength: the tensile strength of slag cement concrete was lower at early ages and higher at later ages. The age at which slag cement concrete tensile strength equaled that for OPC concrete was on average 14 days (Figure 10). The cement source affected the split-tensile strength value at a given age, although the difference among cement sources was not as great for tensile strength as for compressive strength.

**Figure 9.** Split Tensile-Compressive Strength
Relationship for all Ambient Temperature Concrete



**Figure 10.** Split-Tensile Strength with Time;
Average Values for Four Portland Cement Sources

## 5.5  Deicer Scaling Resistance Test Results

### 5.5.1  Deicer Scaling Resistance

Data from deicer scaling resistance testing is quantitatively reported in units of grams per square meter ($g/m^2$), which represents the mass of material lost per unit of exposed surface area.  Three specimens were tested for each combination of materials and curing methods, and an average value for scaling loss was calculated for these three samples at each data collection point (every $5^{th}$ freeze-thaw cycle).  A typical representation of scaling loss over time is provided in Figure 11.  It is evident that the majority of surface scaling occurred at the beginning of testing, and scaling loss leveled off after 20 to 30 cycles.

Average cumulative scaling loss levels after 60 freeze-thaw cycles are reported in Table 19.  While no U.S. standard exists which mandates acceptable levels of scaling loss for slag cement concrete, several other nations do impose limitations which can be considered in this case.  A Swedish standard permits scaling loss of no more than 1,000 $g/m^2$ after 56 cycles, while a Canadian standard sets the limit at 500 $g/m^2$ for 56 cycles (Saric-Coric and Aïtcin, 2002).  No average cumulative scaling loss surpassed the 1,000 $g/m^2$ limit after 60 cycles, and only one set of scaling specimens surpassed the 500 $g/m^2$ limit (Table 19).  The set which exceeded this 500 $g/m^2$ limit was the wet-cured, cement A concrete with igneous coarse aggregate at 50% slag cement replacement, which had an average loss of about 580 $g/m^2$.

In order to determine trends according to variations in materials, data from Table 19 was averaged over slag cement replacement level, cement brand, and coarse aggregate type and is shown according to curing method in Figures 12, 13, and 14, respectively.  As expected, scaling loss generally increased as the level of slag cement increased (Figure 12).  It can also be seen in Figure 12 that concrete cured under wet conditions and with the two commercial curing compounds had the greatest scaling losses after 60 freeze-thaw cycles.[7]  Concrete cured with soda lime and plastic wrap lost the least amount of material, and air-cured concrete fell in between.  Explanations for these trends are provided in Section 5.5.3.

Concrete mixed with cement C had greater cumulative scaling loss than cement A concrete for the air, soda lime, and plastic wrap curing methods (Figure 13).  The scaling loss was more equal for both cement brands for wet, wax, and AMS curing.  Explanations for these trends are provided in Section 5.5.3.  The type of coarse aggregate did not significantly affect the deicer scaling resistance of concrete tested in this study (Figure 14).  In some cases, scaling loss was greater with igneous coarse aggregate, and in other cases, limestone coarse aggregate concrete performed more poorly.  This conclusion is also supported by Deja (2003).

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[7] Scaling loss values were not adjusted to account for the mass of curing compound material that was lost along with surface material.  However, this additional mass of the curing compound is negligible.
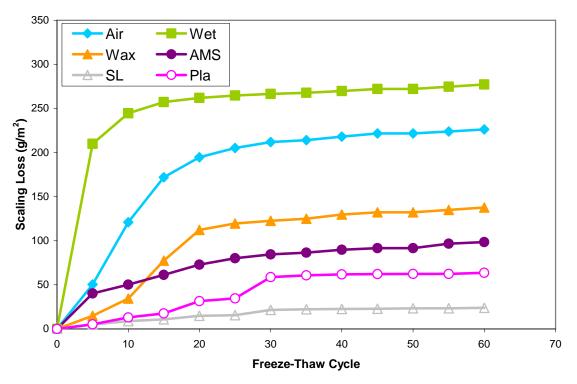
**Figure 11.** Typical Representation of Scaling Loss over Time
Cement C, Limestone, 30% Slag Cement

**Table 19.** Average Cumulative Scaling Loss After 60 Freeze-Thaw Cycles

| Cement | Coarse Aggregate | Slag Cement Replacement | Air | Soda Lime | Plastic Wrap | Wet | Wax | AMS |
|--------|------------------|-------------------------|-----|-----------|--------------|-----|-----|-----|
| A | Limestone | 0% | 12.2 | -- | -- | 22.6 | 28.1 | 23.4 |
| | | 30% | 17.9 | 9.6 | 6.4 | 76.6 | 362.8 | 22.5 |
| | | 50% | 72.7 | 25.8 | 5.0 | 225.2 | 125.9 | 22.0 |
| | Igneous | 0% | 15.5 | -- | -- | 5.3 | 58.3 | 11.7 |
| | | 30% | 8.3 | 3.8 | 1.5 | 50.8 | 103.9 | 36.1 |
| | | 50% | 134.0 | 24.4 | 3.4 | 583.1 | 263.5 | 345.5 |
| C | Limestone | 0% | 77.4 | -- | -- | 63.6 | 36.6 | 40.6 |
| | | 30% | 226.3 | 24.0 | 63.7 | 277.2 | 137.6 | 98.6 |
| | | 50% | 307.1 | 55.9 | 36.0 | 241.5 | 200.5 | 158.4 |
| | Igneous | 0% | 24.9 | -- | 1.7 | 7.5 | 324.1 | 24.3 |
| | | 30% | 74.2 | 114.9 | 53.8 | 66.0 | 190.9 | 83.1 |
| | | 50% | 109.6 | 62.4 | 104.5 | 110.8 | 103.2 | 298.5 |
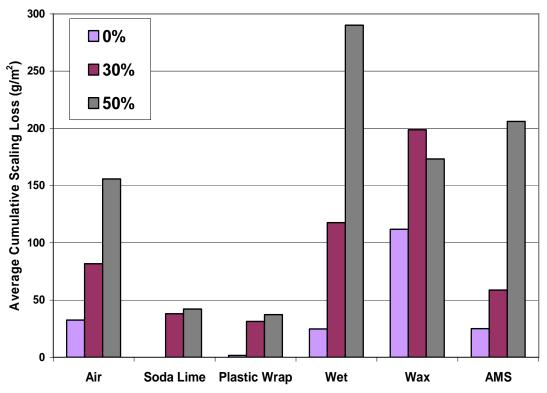
**Figure 12.** Cumulative Scaling Loss after 60 Freeze-Thaw Cycles
Averaged over Slag Cement Replacement
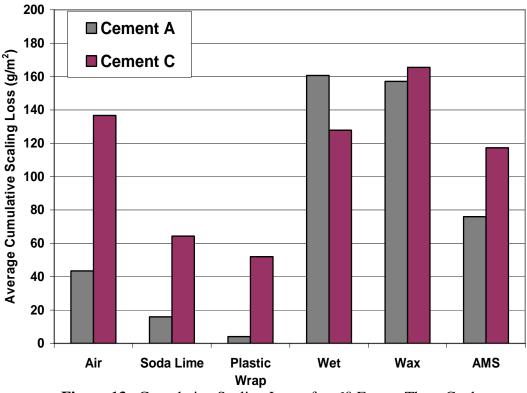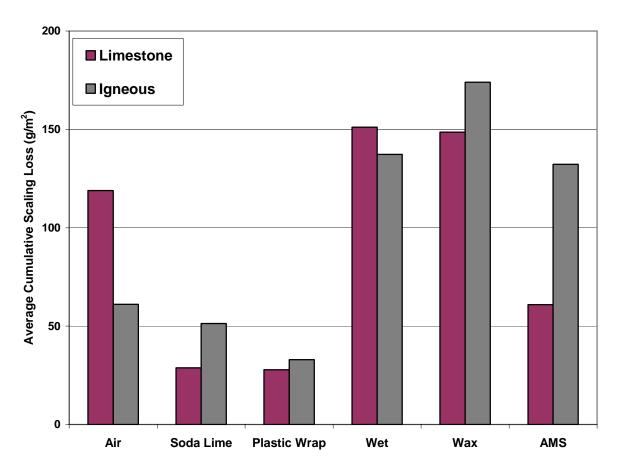


**Figure 13.** Cumulative Scaling Loss after 60 Freeze-Thaw Cycles
Averaged over Cement Brand

**Figure 14.** Cumulative Scaling Loss after 60 Freeze-Thaw Cycles
Averaged over Coarse Aggregate Type

*5.5.2 Carbonation*

One carbonation test specimen was tested for each type of concrete studied. Five test ages were chosen: 14, 28, 40, 60, and 80 days. Depth of carbonation data for the 28 and 80-day tests are provided in Tables 20 and 21. Data for other test ages are provided in Appendix VII. Carbonation data averaged over slag cement replacement level is also shown graphically in Figure 15.

Carbonation occurred to a greater extent after 80 days than after 28 days (Figure 15). This was expected, as carbonation is a time dependent process. This also implies that carbonation continued to progress after 80 days. It is also evident that the carbonation depth recorded at 80 days generally increased as the level of slag cement replacement increased (Figure 15). The carbonation depth in 30% slag cement concrete was on average 1.5 times that of concrete with 0% slag cement, and the carbonation depth of 50% slag cement concrete was about twice that of concrete at the 30% slag cement level. This trend also applies to the carbonation depth recorded at 28 days, but it is less apparent because there was generally very little carbonation observed at 28 days.

In most cases, concrete mixed with cement C had greater carbonation depths at 28 days than did concrete mixed with cement A (Tables 20 and 21).  However, by 80 days, carbonation in cement A concrete had progressed to a value approximately equal to that in cement C concrete.  In some cases, igneous coarse aggregate concrete had greater carbonation levels than limestone concrete (i.e. wet and air-cured concrete), but in many cases, the carbonation level was approximately equal (Tables 20 and 21).

Soda lime pellet application and plastic wrap sealing proved to be very effective at reducing concrete carbonation.  Soda lime pellets and plastic wrap were removed from the carbonation testing blocks after 28 days, so carbon dioxide exposure was permitted at ages greater than 28 days.  Carbonation resistance did not continue after the curing materials were removed.  By 80 days, the soda lime and plastic wrap-cured carbonation specimens had carbonated to levels similar to that of specimens cured under all other curing regimes (Table 21).  Therefore, concrete can be protected from carbonation for only as long as carbon dioxide exposure is limited.[8]  Regarding the other curing regimes, it is noted that in most cases, air-cured concrete carbonated more than wet-cured concrete.  This is consistent with other studies which report that the ideal condition for carbonation to occur is at a relative humidity level of approximately 65% (Papadakis, et al., 1991).  Curing compounds provided good carbonation protection.  Wax and AMS-cured concrete generally had no measured carbonation, even at later ages.

**Table 20.**  Depth of Carbonation at 28 Days, mm

| Cement | Coarse Aggregate | Slag Cement Replacement | Air | Soda Lime | Plastic Wrap | Wet | Wax | AMS |
|--------|------------------|-------------------------|-----|-----------|--------------|-----|-----|-----|
| A | Limestone | 0% | 0 | -- | -- | 0.5 | 0 | 0 |
| | | 30% | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 50% | 0 | 0 | 0 | 0 | 0 | 0 |
| | Igneous | 0% | 0 | -- | -- | 0.4 | 0 | 0 |
| | | 30% | 2.0 | 0 | 0 | 0.4 | 0 | 0 |
| | | 50% | 1.0 | 1.7 | 0 | 0.5 | 0 | 0 |
| C | Limestone | 0% | 0.5 | -- | -- | 0.9 | 0 | 0 |
| | | 30% | 1.0 | 0.2 | 0 | 0.6 | 0 | 0.4 |
| | | 50% | 0.3 | 0 | 0 | 0.6 | 0 | 0.1 |
| | Igneous | 0% | 1.6 | -- | 0.2 | 0.8 | 0 | 0 |
| | | 30% | 2.6 | 0 | 0 | 0.7 | 0 | 0 |
| | | 50% | 2.9 | 0 | 0 | 1.3 | 0 | 0 |

While it is clear from these data that limiting exposure to carbon dioxide reduced carbonation and in turn reduced scaling, there was not a one to tie in all cases.  The introduction of moisture in wet curing and the introduction of curing compounds produced some of the greatest scaling despite not having the largest carbonation depths.

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[8] For scaling block specimens, carbonation is assumed to have been limited even after removal of the soda lime and plastic wrap at 28 days.  The salt solution prevented contact with the atmosphere during freeze-thaw testing.

There is an additional mechanism at working scaling resistance which this research was unable to establish.

**Table 21.** Depth of Carbonation at 80 Days, mm

| Cement | Coarse Aggregate | Slag Cement Replacement | Air | Soda Lime | Plastic Wrap | Wet | Wax | AMS |
|---|---|---|---|---|---|---|---|---|
| A | Limestone | 0% | 0.5 | -- | -- | 0.8 | 0 | 0 |
| | | 30% | 1.75 | 0.6 | 0.6 | 0.8 | 0 | 0.2 |
| | | 50% | 0.2 | 1.5 | 2.0 | 0.3 | 0 | 0 |
| | Igneous | 0% | 3.4 | -- | -- | 1.8 | 0 | 2.8 |
| | | 30% | 3.1 | 2.8 | 2.0 | 1.2 | 0 | 0 |
| | | 50% | 5.9 | 3.9 | 1.1 | 2.3 | 4.6 | 0 |
| C | Limestone | 0% | 0.2 | -- | -- | 0.7 | 0 | 0 |
| | | 30% | 0.3 | 0.3 | 0.2 | 0.8 | 0 | 0.4 |
| | | 50% | 0.5 | 1.0 | 2.0 | 1.3 | 0 | 0.3 |
| | Igneous | 0% | 1.6 | -- | 0.3 | 1.2 | 0 | 0 |
| | | 30% | 2.9 | 1.8 | 1.0 | 1.7 | 0 | 0 |
| | | 50% | 4.5 | 3.8 | 1.6 | 2.7 | 0 | 0 |
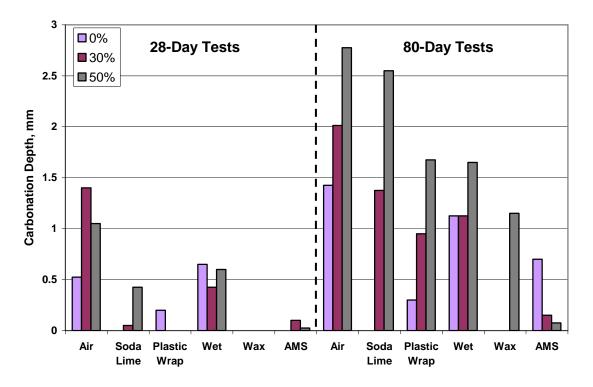


**Figure 15.** Carbonation Depth Averaged over Slag Cement Replacement Level

### 5.5.3 Correlation between Carbonation and Scaling

Based on previous research, knowledge of the hydration properties of OPC and slag cement, and data from this study, a correlation can be made between deicer scaling resistance and carbonation.

The correlation begins with OPC hydration. The well known contributors to OPC hydration are tricalcium silicate ($C_3S$) and dicalcium silicate ($C_2S$), which react according to the following mass-balanced formulas: (Neville, 1996)

$$2C_3S + 6H_2O \rightarrow C\text{-}S\text{-}H + 3Ca(OH)_2 \quad \text{and} \qquad \text{(Equation 5)}$$
$$2C_2S + 4H_2O \rightarrow C\text{-}S\text{-}H + Ca(OH)_2. \qquad \text{(Equation 6)}$$

Thus, along with calcium silicate hydrate (C-S-H), calcium hydroxide ($Ca(OH)_2$) is a major reaction product of OPC hydration.

Addition of slag cement to the mix leads to a change in the overall hydration process. When slag cement is mixed with water, a small amount of hydration takes place immediately. However, soon after this initial reaction, a coating of silica and alumina forms around the slag particles. Activating agents are then required to break down the inhibitive coating and allow slag cement hydration to continue (Roy, 1989). When OPC is present, calcium hydroxide created by reactions (1) and (2) serves as such an activator and allows for continued slag cement hydration. Increasing the replacement level of slag cement for OPC therefore results in a decrease in the concentration of calcium hydroxide present in the paste:

$$\uparrow \text{slag cement} \rightarrow \downarrow Ca(OH)_2. \qquad \text{(Equation 7)}$$

The decrease is two-fold; a higher replacement level of slag cement requires more calcium hydroxide for activation, while the simultaneous decrease in OPC results in less calcium hydroxide production. This phenomenon has been previously demonstrated by Sulapha, et. al., and Hill and Sharp (Sulapha, et. al, 2003; Hill and Sharp, 2002).

Concrete carbonation enters the correlation in the following way. Carbonation occurs when atmospheric carbon dioxide diffuses into the concrete surface and reacts with compounds in the cement paste to form calcium carbonate. Reaction agents include calcium hydroxide and calcium-silicate-hydrate. Reaction products include calcium carbonate ($CaCO_3$) and calcium carbonate-silicate-hydrate ($3\ CaCO_3 \cdot 2\ SiO_2 \cdot 3\ H_2O$) These carbonation reactions are as follows: (Sulapha, et. al, 2003; Meyers, 1949)

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad \text{and} \qquad \text{(Equation 8)}$$
$$C\text{-}S\text{-}H + CO_2 \rightarrow 3\ CaCO_3 \cdot 2\ SiO_2 \cdot 3\ H_2O. \qquad \text{(Equation 9)}$$

The reaction (8) with calcium hydroxide takes place preferentially (Sulapha, et. al, 2003). In slag cement concrete, however, there is less calcium hydroxide available to complete this reaction (Equation 7), and consequently, the reaction (9) involving carbonation of C-S-H also occurs:

$$\downarrow Ca(OH)_2 \rightarrow \uparrow C\text{-}S\text{-}H \text{ carbonation.} \qquad \text{(Equation 10)}$$

Conversely, in OPC concrete, very little C-S-H carbonation occurs because calcium hydroxide is readily available to complete the reaction (8).

Both carbonation reactions (8) and (9) result in changes in material structure at the exposed surface of the hardened concrete. The reaction (8) results in a net increase in volume in the paste, as the calcium carbonate molecule is larger than the calcium hydroxide molecule which it replaces (Neville, 1996). A net decrease in volume occurs when the reaction (9) takes place (Copuroglu, et. al, 2004). These changes in material volume have been verified in several studies relating the effect of carbonation to the porosity of cement paste. Carbonation causes a decrease in porosity in OPC concrete but an increase in porosity in slag cement concrete (Claisse, et. al, 1999; Houst and Wittmann, 1994; Pihlajavaara, 1968; De Ceukelaire and Van Nieuwenburg, 1993). The increased porosity in slag cement concrete is a result of the carbonation of C-S-H:

$\uparrow$ C-S-H carbonation $\rightarrow$ $\uparrow$ porosity. (Equation 11)

The increase in surface porosity of slag cement concrete caused by C-S-H carbonation allows carbon dioxide to penetrate more easily into the surface. In addition, any remaining calcium hydroxide in the paste is more susceptible to carbonation as carbon dioxide penetrates farther into the surface. Therefore, the carbonation reactions occur at greater depths below the exposed surface in slag cement concrete, and the depth of total carbonation is greater:

$\uparrow$ porosity $\rightarrow$ $\uparrow$ total carbonation. (Equation 12)

This phenomenon has been previously demonstrated for fly ash concrete by Atiş (2004).

The changes in materials and porosity described above cause a restructuring of the pore system in the portions of the concrete where carbonation has occurred. This restructuring has a direct effect on the freeze-thaw resistance of concrete, as a sound pore structure is necessary to accommodate water as it freezes and expands. Concrete carbonation thereby contributes to decreased deicer scaling resistance:

$\uparrow$ total carbonation $\rightarrow$ $\downarrow$ scaling resistance. (Equation 13)
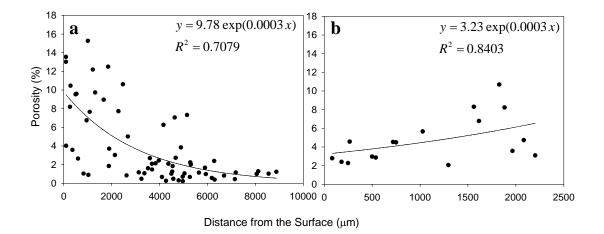
Relating equations (7) and (10) through (13) yields a phenomenological model for the decreased scaling resistance noted in concrete made with slag cement:
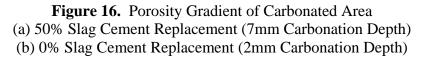
$\uparrow$ slag cement $\rightarrow$ $\downarrow$ $Ca(OH)_2$  (Equation 7)
$\downarrow$ $Ca(OH)_2$ $\rightarrow$ $\uparrow$ C-S-H carbonation  (Equation 10)
$\uparrow$ C-S-H carbonation $\rightarrow$ $\uparrow$ porosity  (Equation 11)
$\uparrow$ porosity $\rightarrow$ $\uparrow$ total carbonation  (Equation 12)
$\uparrow$ total carbonation $\rightarrow$ $\downarrow$ scaling resistance  (Equation 13)

Equations (10) through (13) can be verified using data gathered in this study:

- $\downarrow$ $Ca(OH)_2$ $\rightarrow$ $\uparrow$ C-S-H carbonation  (Equation 10)

Differences in chemistry and carbonation behavior of cements A and C support Equation (10). Cement C had a lower concentration of $C_3S$ than cement A (Table III.1, Appendix III). Therefore, according to Equations (5) and (6), cement C produced a lesser amount of $Ca(OH)_2$ than cement A. In addition, cement C concrete carbonated to a greater depth than cement A concrete. It is known that, when $Ca(OH)_2$ is in limited supply, C-S-H carbonation occurs (Equation 9). Therefore, cement C concrete underwent a greater degree of C-S-H carbonation than cement A due to a lower level of available $Ca(OH)_2$.

Equation (10) is also supported based on carbonation data for concrete containing varying levels of slag cement. As the amount of slag cement in the mix increased, the level of carbonation also increased (Tables 20 and 21). Increasing the level of slag cement also decreases the amount of available $Ca(OH)_2$ (Equation 7). Therefore, slag cement concrete underwent a greater degree of C-S-H carbonation than OPC concrete due to a lower level of available $Ca(OH)_2$.

- $\uparrow$ C-S-H carbonation $\rightarrow$ $\uparrow$ porosity           (Equation 11)

Equation (11) was verified through a series of additional tests performed at the University. Scanning electron microscopy (SEM) was used to measure the porosity of two types of concrete: 50% slag cement concrete and OPC concrete. The tests were performed when the concrete was 16 months old and had carbonated to depths of 7mm and 2mm, respectively. The porosity gradient in the carbonated area of each sample is shown in Figure 16. The porosity of the OPC concrete was less than half that of the slag cement concrete up to 1000µm, where carbonation had occurred in both samples. Therefore, the C-S-H carbonation which occurred in the slag cement concrete caused an increase in porosity compared to the effects of $Ca(OH)_2$ carbonation which occurred in OPC concrete.



**Figure 16.** Porosity Gradient of Carbonated Area
(a) 50% Slag Cement Replacement (7mm Carbonation Depth)
(b) 0% Slag Cement Replacement (2mm Carbonation Depth)

## 5.6 Air Dry Shrinkage

In general, the addition of slag cement did not cause a significant change in concrete shrinkage compared to OPC concrete. Table 22 shows the average shrinkage of three specimens for each concrete mix, and the percentage of shrinkage for the slag cement concretes compared to OPC concretes. In about half of the cases, shrinkage with slag cement concrete was greater than OPC concrete. Based on the average of all portland cement sources, slag cement concrete shrinkage was quite similar to OPC concrete shrinkage (Table 22). Overall, limestone aggregate concretes had lower levels of

shrinkage than igneous aggregate concretes.  The 56-day shrinkage results at 40°F compared with the ambient temperature shrinkage for cement D are provided in Table 23. At 40°F, less shrinkage occurred in slag cement concrete than in OPC concrete; the opposite was generally true for ambient temperature concrete (Tables 22 and 23).  The 40°F concrete had lower levels of shrinkage than the ambient temperature concrete, especially igneous coarse aggregate was used.

**Table 22.**  Average 120-day Shrinkage of Ambient Temperature Concretes

| Cement | Aggregate | Slag Cement | 120-day Shrinkage (%) | Percentage of 0% Mix |
|--------|-----------|-------------|----------------------|---------------------|
| A | Limestone | 0% | 0.0420 | 100% |
| | | 30% | 0.0630 | 150% |
| | | 50% | 0.0603 | 144% |
| | Igneous | 0% | 0.0497 | 100% |
| | | 30% | 0.0553 | 111% |
| | | 50% | 0.0553 | 111% |
| B | Limestone | 0% | 0.0400 | 100% |
| | | 30% | 0.0417 | 104% |
| | | 50% | 0.0405 | 101% |
| | Igneous | 0% | 0.0460 | 100% |
| | | 30% | 0.0490 | 107% |
| | | 50% | 0.0500 | 109% |
| C | Limestone | 0% | 0.0523 | 100% |
| | | 30% | 0.0437 | 83% |
| | | 50% | 0.0423 | 81% |
| | Igneous | 0% | 0.0543 | 100% |
| | | 30% | 0.0510 | 94% |
| | | 50% | 0.0520 | 96% |
| D | Limestone | 0% | 0.0390 | 100% |
| | | 30% | 0.0310 | 79% |
| | | 50% | 0.0327 | 84% |
| | Igneous | 0% | 0.0637 | 100% |
| | | 30% | 0.0757 | 119% |
| | | 50% | 0.0567 | 89% |
| Average | Limestone | 0% | 0.0433 | 100% |
| | | 30% | 0.0448 | 103% |
| | | 50% | 0.0440 | 101% |
| | Igneous | 0% | 0.0534 | 100% |
| | | 30% | 0.0578 | 108% |
| | | 50% | 0.0535 | 100% |

**Table 23.** Average 56-day Shrinkage of Cement D Concretes
at Ambient Conditions and 40°F

| Cement | Aggregate | Slag Cement (%) | 56-day Shrinkage (%) | Percentage of 0% Mix |
|--------|-----------|-----------------|----------------------|----------------------|
| D (72°F) | Limestone | 0% | 0.0317 | 100% |
| | | 30% | 0.0257 | 81% |
| | | 50% | 0.0250 | 79% |
| | Igneous | 0% | 0.0557 | 100% |
| | | 30% | 0.0670 | 120% |
| | | 50% | 0.0480 | 86% |
| D (40°F) | Limestone | 0% | 0.0280 | 100% |
| | | 30% | 0.0235 | 84% |
| | | 50% | 0.0233 | 83% |
| | Igneous | 0% | 0.0350 | 100% |
| | | 30% | 0.0300 | 86% |
| | | 50% | 0.0290 | 83% |

## 5.7  Comparison of Grade 120 and Grade 100 Slag Cement Concrete

The results of this study were compared to data from WHRP Study #0092-02-14a (Cramer and Sippel 2005) in which a similar testing matrix was studied using grade 100 slag cement.  Direct comparisons of the magnitudes the results between the studies were avoided due to the fact that slightly different concrete mix constituents were used in the two studies.  The results presented here are relative to each study and comparisons between studies were made based on the values of slag cement concretes relative to OPC concretes within each study.

### 5.7.1  Background Information

The results of this study were compared to data from WHRP Study #0092-02-14a (Cramer and Sippel 2005) in which a similar testing matrix was studied using grade 100 slag cement.  This study will be referred to as Phase I, and the current study using grade 120 slag cement will be referred to as Phase II.  Cement sources were similar between Phases I and II, as were types of coarse aggregate.  Materials for Phases I and II, however, were acquired at different times.  While it was not expected that materials acquired for each phase would perform identically, slight variations were not expected to create a large difference in the parameters in this study.

Compressive strength values were used to determine whether a direct comparison could be made between phases:  it was postulated that because coarse aggregate and cement sources were similar, OPC strength values (i.e. those with no slag cement replacement) should be similar.  Compressive strength values averaged over cement source are shown in Figures 17(a) and 17(b) for limestone and igneous coarse aggregates, respectively. Concrete made with igneous coarse aggregate had similar strengths for both Phases

(Figure 17(b)), but Phase II strength values were higher than Phase I values for limestone coarse aggregate (Figure 17(a)).

To determine a reason for the difference in limestone concrete strength values, factors which influence the w/cm ratio (and thus compressive strength) were investigated. Mix water was calculated based on w/cm = 0.45 and adjusted to account for aggregate absorption factors. The aggregate absorption factors used in both phases are given in Table 24. The absorption factors from Phase I are higher for all three aggregate materials, with the limestone coarse aggregate value differing the most. Some variation is to be expected in these values: the aggregate shipments, while similar in material properties, came at different times, and different operators performed the test in each phase. To provide an idea for the magnitude of permissible differences between Phase I and Phase II values, assuming similar materials, the final column of Table 24 provides data for the acceptable range of two absorption test results. These values are taken from ASTM C127-98 and ASTM C128-01 for coarse aggregate absorption and fine aggregate absorption calculations, respectively.

According to the ASTM values for acceptable range of two test results, igneous coarse aggregate and fine aggregate absorption values were within the permissible range of variation. Absorption values from Phases I and II for limestone coarse aggregate, however, were not within the permissible range: the difference between values was 0.71%, while the permissible difference is 0.41% (Table 24). This variation in limestone absorption value was noted when the Phase II absorption values were determined. The test was repeated several times with the Phase II aggregates to ensure that correct values were recorded. Because the 1.97% limestone absorption value was repeatable in Phase II, it was hypothesized that the Phase I value of 2.68% was high.

When a high aggregate absorption value is used in mix design, there is additional water present in the mix that is not absorbed by the aggregate. The amount of water available for hydration increases, thus increasing the effective w/cm ratio. A higher than anticipated w/cm ratio results in lower than anticipated compressive strength values.

For example, in a typical 3.0 ft$^3$ mix, 28.2 pounds of water is required to achieve the target w/cm = 0.45. If the 2.68% absorption value were used, the amount of water added to the mix would increase to 34.8 pounds. If the actual absorption value was 1.97%±0.41% (adjusted for the ASTM C127-98 acceptable range of variation), 33.3±0.8 pounds of water is truly required to achieve the target w/cm = 0.45. The additional water available due to the high absorption value would increase the actual w/cm ratio to 0.47±0.02. An increase in w/cm from 0.45 to 0.49 can cause a 10% decrease in concrete strength at 28 days (Kosmatka, et. al, 2002). Indeed, the Phase I compressive strength values for concrete made with limestone coarse aggregate were 10% to 20% lower than the corresponding Phase II compressive strength values. However, we cannot be certain this was the cause of the difference and those researchers who have tried to produce identical concrete over a period of years recognize the difficulty of this task.

These uncertainties regarding the coarse aggregate absorption and the w/cm ratio discounts a direct comparison between Phase I and Phase II limestone coarse aggregate concrete. Therefore, the comparisons made in the following sections for grades 100 and 120 slag cement concrete are based on the differences in characteristics between slag cement concrete and OPC concrete in individual phases. For instance, compressive strength is compared using a percentage of OPC strength criterion. This is a valid comparison, as the w/cm ratio was consistent in each individual phase among mixes of the same coarse aggregate type.
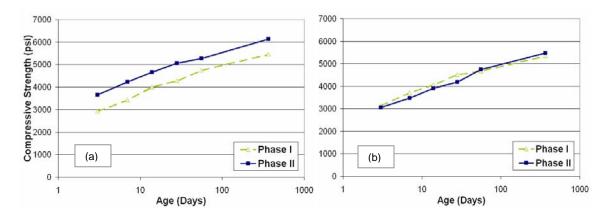


**Figure 17.** Average Phase I and Phase II Compressive Strength with Time for
(a) Limestone Coarse Aggregate and (b) Igneous Coarse Aggregate

**Table 24.** Aggregate Absorption Values

| Material | Phase I | Phase II | Difference Between Phases | ASTM Acceptable Range of Two Results, Multi-laboratory Precision |
|---|---|---|---|---|
| Limestone coarse aggregate | 2.68% | 1.97% | 0.71% | 0.41% |
| Igneous coarse aggregate | 1.35% | 1.25% | 0.10% | 0.41% |
| Fine aggregate | 0.85% | 0.72% | 0.13% | 0.66% |

*5.7.2  Compressive Strength Comparison*

Comparison of compressive strength data from Phases I and II reveals that, relative to OPC concrete, grade 120 slag cement concrete gained strength more quickly than did grade 100 slag cement concrete. This was expected: by definition grade120 slag cement is more active and hydrates faster than grade 100 slag cement (ASTM C989). Figures 18 and 19 compare percentage of OPC concrete compressive strength for grades 100 and

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120 slag cement concrete. The data represent all four OPC sources, and limestone and igneous coarse aggregate strengths are reported in Figures 18 and 19, respectively. Grade 120 slag cement concrete had lower strengths at 3 and 7 days compared to OPC concrete, but at 14 days and beyond, grade 120 slag cement concrete strength was equal to or greater than that of OPC concrete, regardless of coarse aggregate type (Figures 18 and 19). Grade 100 slag cement concrete strength was equal to OPC concrete strength after 28 days when limestone coarse aggregate was used (Figure 18). When igneous coarse aggregate was used, however, grade 100 slag cement concrete strength never equaled that of OPC concrete (Figure 19). At the final test age (365 days), 30% and 50% grade 100 slag cement concrete with igneous coarse aggregate had strengths that were 95% and 90% of OPC concrete, respectively.
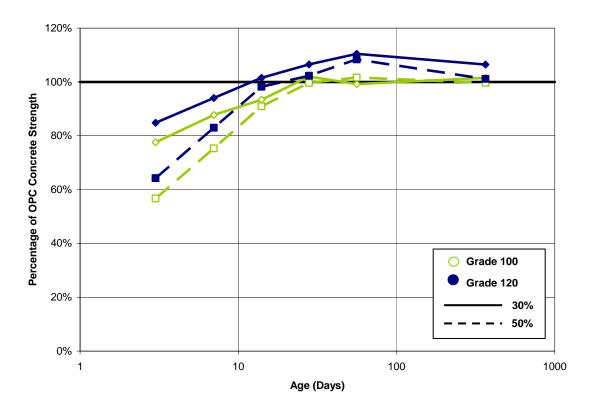


**Figure 18.** Comparison of Average Slag Cement Concrete Compressive Strength to Average OPC Concrete Strength for Grades 100 and 120 Slag Cement Limestone Coarse Aggregate
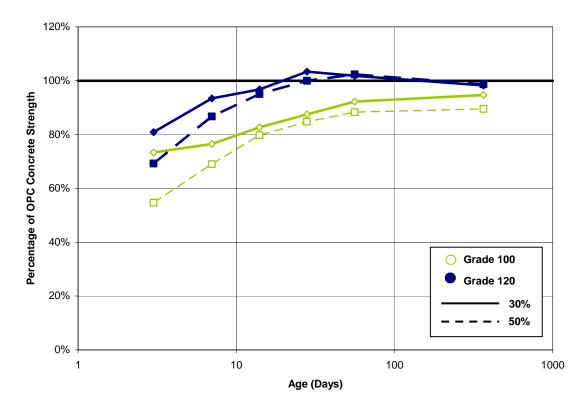
**Figure 19.** Comparison of Average Slag Cement Concrete Compressive Strength to Average OPC Concrete Strength for Grades 100 and 120 Slag Cement Igneous Coarse Aggregate

### 5.7.3 Deicer Scaling Resistance Comparison

To compare the deicer scaling resistance performance of grade 120 slag cement concrete to grade 100 slag cement concrete from WHRP Study #0092-02-14a, cumulative scaling loss for each replacement level was compared to OPC concrete scaling loss. The data, reported as the amount of increase in scaling loss over OPC concrete, is shown in Figure 20. For air and wet-cured concrete, the increase in scaling loss for slag cement concrete compared to OPC concrete was greater for grade 100 slag cement than for grade 120 slag cement. For instance, 30% grade 100 wet-cured concrete had 30 times the scaling loss as OPC concrete, while similar concrete made with grade 120 slag cement had a factor of increase of about 7 (Figure 20). The increase over OPC concrete was not significant for wax-cured concrete for either grade of slag cement. This is due to the fact that wax-cured concrete had poor scaling resistance for both grades of slag cement at all replacement levels, including 0% replacement (Figure 12).

In other areas, however, trends were similar for grades 100 and 120 concrete. For concrete made with both grades of slag cement, scaling loss increased with an increase in replacement level. Rates of scaling were also similar, with the largest scaling loss occurring during the first 25 to 35 freeze-thaw cycles, followed by a decrease in the rate

of scaling.  Trends according to changes in coarse aggregate type were not evident for grade 100 slag cement concrete, nor were they apparent in the current study (Cramer and Sippel, 2005).
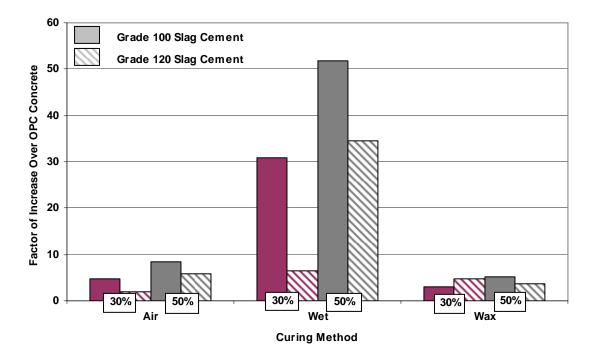


**Figure 20.**  Cumulative Scaling Loss for Grades 100 and 120 Slag Cement Concrete Compared to OPC Concrete Scaling Loss


## 6.  Summary of Findings and Guidelines on Use

### 6.1  Summary of Findings

Use of slag cement in highway pavement concrete is desirable because of its status as an environmentally friendly, recycled material and the economic advantages in reducing overall cement expenditures.  This study investigated the feasibility of using grade 120 slag cement as a substitute for OPC at replacement levels up to 50% by mass.  Strength and deicer scaling resistance properties were studied for concrete incorporating grade 120 slag cement at 0%, 30%, and 50% replacement levels.  It was determined that grade 120 slag cement replacement up to and including 50% is acceptable when the mixing and curing temperature is greater than 40°F.  Grade 120 slag cement concrete mixed and cured at 40°F did not gain strength quickly enough in the laboratory to conclude that roadways may be opened to traffic in an acceptable amount of time.  Concrete containing grade 120 slag cement has lower deicer scaling resistance than OPC concrete.  However, concrete scaling resistance was acceptable at all slag cement replacement levels.  Greater scaling resistance was provided by certain curing methods, specifically those which limited carbon dioxide exposure.  Variations in the fineness and chemistry of Type I

portland cement resulted in differences in strength and deicer scaling resistance from case to case. The type of coarse aggregate used affected the strength properties of grade 120 slag cement concrete but did not have a significant effect on the concrete's deicer scaling resistance.

## 6.2 Slag Cement Grade Guidelines

Grade 120 slag cement was studied in the current project. A similar study conducted prior to the current project researched the use of grade 100 slag cement (Cramer and Sippel, 2005). Based on results from both studies, properly cured grade 120 slag cement concrete provides performance comparable to OPC concrete after a short latent hydration lag period, and grade 100 slag cement concrete provides less comparable performance with greater latent hydration lag periods.

Grade 120 slag cement has greater hydraulic activity with OPC than does grade 100 slag cement, as indicated by higher slag activity index values and higher rates of strength gain measured in the current study. This means that grade 120 slag cement concrete pavement can be opened to traffic after a shorter waiting period than grade 100 slag cement concrete pavement. In addition, it was found that the strength of grade 120 slag cement concrete equaled that of OPC concrete after 14 days, whereas grade 100 slag cement concrete required 28 days (limestone coarse aggregate) or did not reach a strength equal to OPC concrete during the duration of the study (igneous coarse aggregate).

It was also found that grade 120 slag cement concrete had a significantly higher level of deicer scaling resistance than did grade 100 slag cement concrete. According to international standards for acceptable levels of scaling loss, grade 120 slag cement concrete performed adequately in all cases. Grade 100 slag cement concrete, on the other hand, did not perform adequately in many cases, and the increase in scaling loss as compared to OPC concrete was much greater than when grade 120 slag cement was used.

## 6.3 Strength Guidelines

For data gathered in this study, a plot of concrete compressive strength versus age results in a non-linear curve on a log scale for ages greater than 56 days. The non-linearity is more pronounced for slag cement concrete than for OPC concrete. To develop a predictive model for strength at a given age, the strength-age curve was fit to the following non-linear log model:

$$f_c(t) = A \left[ Log_{10}(t) \right]^2 + B \left[ Log_{10}(t) \right] + C \qquad \text{(Equation 14)}$$

Where $t$ is the age of the concrete in days, and $f_c(t)$ represents the compressive strength at age $t$. The coefficients $A$, $B$, and $C$ were developed for concrete made with both types of coarse aggregate at 0%, 30%, and 50% replacement with grade 100 and grade 120 slag cements. These coefficients are listed in Table 25. A plot of Equation 14 for each type

of concrete is provided in Figures 21 and 22 for grades 100 and 120 slag cement, respectively.

The curves in Figures 21 and 22 have been plotted at ages earlier than 72 hours (3 days) so that a theoretical "zero" strength point could be evaluated.  Although early-age strength will not precisely follow the relationship given in Equation 14, this method indicates how the strength gain of slag cement concrete is delayed in comparison to OPC concrete.  It is clear that initially, the compressive strength at a given age decreases with increasing slag cement replacement for both grades 100 and 120.  The slopes of the strength-time curves are greater for grade 120 slag cement concrete than for OPC concrete, indicating that the strength of slag cement concrete will eventually equal or surpass that of OPC concrete (Figure 22).  The slopes of the strength-time curves for grade 100 slag cement concrete, however, are approximately equal to that for OPC concrete.  Therefore the strength of concrete made with grade 100 slag cement is generally less than or equal to that for OPC concrete.

Strength of grade 120 slag cement concrete equals and surpasses that of OPC concrete at approximately 14 days (Figure 22).  Compressive strength of grade 100 slag cement concrete made with limestone aggregate equals that of OPC concrete between 28 and 56 days, while the strength of the same concrete made with igneous aggregate does not achieve strengths similar to OPC concrete (Figure 21).

Equation 14 predicts higher compressive strength for OPC concrete with limestone coarse aggregate in Figure 22 than it does in Figure 21.  This anomaly may be due to small differences in the w/cm ratio tracking from aggregate absorption  and was discussed in Section 5.7.1.

The following guidelines relating to strength can be concluded from this study:

- Grade 120 slag cement concrete with 30% and 50% replacement achieve strengths similar to that of OPC concrete by an age of 14 days.
- Grade 100 slag cement concrete with 30% and 50% replacement and limestone coarse aggregate achieved strength similar to that of OPC concrete between the ages of 28 and 56 days.  Grade 100 slag cement concrete with igneous coarse aggregate did not achieve 100% of OPC strength during the duration of the Phase I study.
- Use of limestone crushed rock for coarse aggregate results in slightly stronger (15% to 20%) concrete than when igneous river gravel is used.
- The tensile to compressive strength ratio of grade 120 slag cement concrete is similar to that of OPC concrete.
- The rate of strength gain for slag cement concrete is controlled by the slag cement replacement level and by the fineness and chemistry of the OPC with which it is used.
- Due to the decrease in rate of strength gain for concrete mixed and cured at 40°F, a seasonal restriction is warranted for use of grade 120 slag cement in highway pavement concrete.  Slag cement should be used only between April 15th and

October 15<sup>th</sup>, when average daily temperatures in the state are reliably greater than 40°F.

**Table 25.** Coefficients A, B, and C for Equation 14

| Slag Cement | Coeff. | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|---|
| | | 0% | 30% | 50% | 0% | 30% | 50% |
| Grade 100 | A | -222.9 | -468.9 | -801.7 | -257.9 | -297.3 | -583.7 |
| | B | 1906 | 3016 | 4301 | 1829 | 2265 | 3250 |
| | C | 2051 | 898.5 | -291.6 | 2338 | 1228 | 282.1 |
| Grade 120 | A | -175.2 | -601 | -979 | -95.9 | -487 | -594 |
| | B | 1705 | 3501 | 4846 | 1482 | 2902 | 3409 |
| | C | 2908 | 1526 | 223 | 2333 | 1161 | 590 |
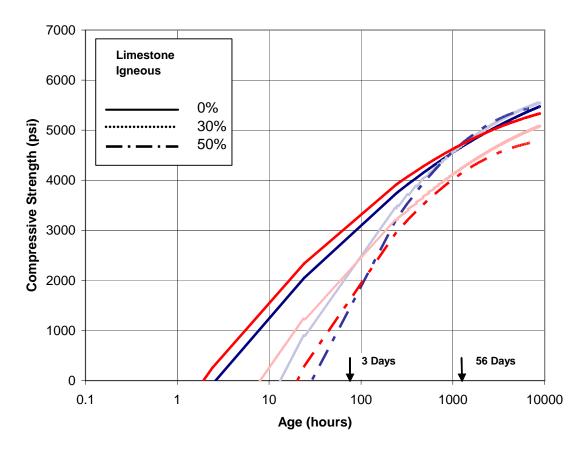


**Figure 21.** Compressive Strength versus Concrete Age According to Equation 14, Grade 100 Slag Cement

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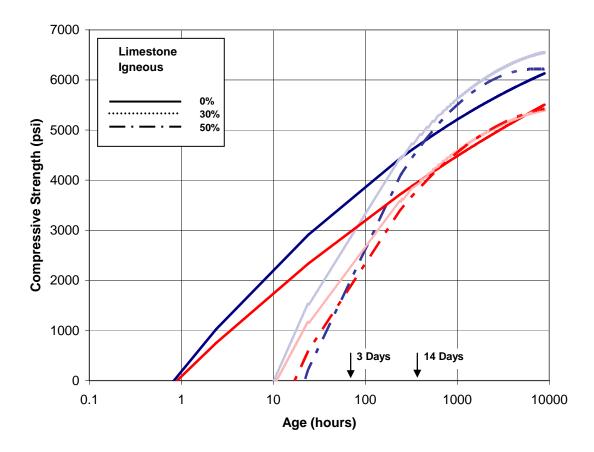
**Figure 22.** Compressive Strength versus Concrete Age According to Equation 14, Grade 120 Slag Cement

## 6.4 Deicer Scaling Resistance Guidelines

Because of the scope of materials used in the various concrete mixes, it is difficult to establish predictive equations for deicer scaling resistance. Many variables affect the degree of scaling resistance, including curing method, slag cement replacement level, and source of portland cement. However, with each of these variables in mind, it is possible to establish qualitative guidelines based on scaling resistance for use of slag cement in highway pavement concrete:

- Grade 120 slag cement concrete has adequate deicer scaling resistance at replacement levels of 30% and 50%.[9]
- Concrete containing grade 100 slag cement should not be expected to perform at a level comparable to OPC concrete with regard to scaling resistance.
- Concrete treated with curing compounds performs poorly with slag cement concrete and, in some cases, with OPC concrete. Further research is warranted to

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[9] Based on international standards.

determine the mechanism which causes the decrease in scaling resistance as this loss in durability cannot be tied one to one to increased carbonation.

- For concrete cured under conditions where atmospheric carbon dioxide exposure was not limited, ambient laboratory conditions resulted in concrete with the greatest scaling resistance. Scaling loss was not improved for wet-cured concrete.
- Compared to all other curing methods, concrete cured under low carbon dioxide exposure demonstrates the highest level of scaling resistance. Carbonation is the likely cause of decreased resistance for concrete cured under normal levels of carbon dioxide exposure.
- Deicer scaling resistance is affected by the chemistry of the portland cement, specifically by the compositions of tri- and di-calcium silicates.
- Concrete made with limestone and igneous coarse aggregates demonstrate similar levels of deicer scaling resistance.

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## Appendix II  Synthesis of Bibliography

**Air Entrainment**

| Concept | Reference |
|---|---|
| Compared to OPC concrete, slag cement concrete requires higher doses of air entrainment to achieve a specific fresh air content. | Fernandez and Malhotra,1990<br><br>Malhotra, 1983 |
| For concrete containing mineral admixtures, the entrained air content is reduced as the temperature increases. | Rajamane, et. al, 2002 |
| The microstructure of slag cement paste is denser than OPC paste and develops more fine pores. | Roy, 1989 |

**Chemistry and Hydration of Slag Cement**

| Concept | Reference |
|---|---|
| The chemical components of slag cement are similar to OPC, but with different compositions.  This results in a different hydration process for slag cement. | ACI Committee 233R, 2004<br>Neville, 1996<br>Hewlett, 2004 |
| Calcium hydroxide formed during OPC hydration and other alkaline compounds serve as activators and allow for continued hydration of the slag cement. | Roy, 1989<br><br>Saeki and Monteiro, 2005 |
| Calcium hydroxide is the most prevalent activator.  Increasing the concentration of calcium hydroxide increases the rate of slag cement hydration. | Biernacki, et. al, 2002<br><br>Saeki and Monteiro, 2005 |
| Due to consumption as an activator, the concentration of calcium hydroxide in slag cement concretes is significantly lower than that in OPC concretes. | Sulapha, et. al, 2003<br><br>Hill and Sharp, 2002 |

**Concrete Carbonation**

| Concept | Reference |
|---|---|
| Atmospheric carbon dioxide diffuses into the concrete and reacts with calcium hydroxide (preferentially), or calcium-silicate-hydrate to form calcium carbonate. | Meyers, 1949<br><br>Sulapha, et. al, 2003 |
| Carbonation causes a restructuring of the concrete's pore system. | Neville, 1996<br>Copuroglu, et. al, 2004 |
| Porosity of OPC concrete is decreased due to carbonation. | Claisse, et. al, 1999<br>Houst and Wittmann, 1994<br>Pihlajavaara, 1968 |
| Porosity of slag cement concrete is increased due to carbonation. | De Ceukelaire and Van Nieuwenburg, 1993 |
| Carbonation causes a decrease in deicer scaling resistance, especially in slag cement concrete. | Stark and Ludwig, 1997<br>Copuroglu, et. al, 2004 |
| Slag cement concrete is more susceptible to carbonation than is OPC concrete. | Litvan and Meyer, 1986<br>Osborne, 1986 |

**Curing Method and Temperature**

| Concept | Reference |
|---|---|
| Curing compounds do not protect concrete from deicer scaling loss. | Sippel, 2004<br><br>Mason, 2003<br><br>Afrani and Rogers, 1994 |
| Concrete cured in high carbon dioxide environments has lower deicer scaling resistance than concrete cured under normal levels of carbon dioxide. | Copuroglu, et. al, 2004<br><br>Stark and Ludwig, 1997 |
| The strength gain of concrete in cold weather is significantly slowed. | Wimpenney, et. al, 1989<br>Eren, 2002 |
| Fineness may effect the strength development of slag cement concrete mixed and cured at cold temperatures. | Miura and Iwaki, 2000 |

**Deicer Scaling Resistance**

| Concept | Reference |
|---|---|
| Cracking of concrete due to freezing water expansion occurs mainly in the capillary pores. | Neville, 1996 |
| Deicing agents exacerbate the freeze-thaw problem due to additional osmotic pressures applied in the pore system. | Neville, 1996<br>Mather, 1979 |
| Slag cement concrete has a lower resistance to scaling than does OPC concrete. | Stark and Ludwig, 1997<br>Afrani and Rogers, 1994 |
| Slag cement concrete with no air entrainment has a lower deicer scaling resistance than slag cement concrete with air entrainment. | Deja, 2003<br><br>Stark and Ludwig, 1997 |
| The type of coarse aggregate used does not have a significant effect on deicer scaling resistance. | Deja, 2003 |

**Drying Shrinkage**

| Concept | Reference |
|---|---|
| Conflicting evidence exists regarding the effect of slag cement on drying shrinkage of concrete. Some studies suggest the shrinkage increases with the addition of slag cement, while others showed no difference in shrinkage for OPC and slag cement concretes. | Tanzawa, et. al, 1989<br><br>Hogan and Meusel, 1981 |
| For similar w/cm ratios, slag cement concrete will have increased shrinkage, but shrinkage will be similar to OPC if the w/cm ratio is reduced (i.e. to maintain similar workability). | Brooks and Neville, 1992 |

**Manufacturing of Slag Cement**

| Concept | Reference |
|---|---|
| Slag cement variability is low from a single producer but can be higher among producers | Malhotra, 1987<br>Hewlett, 2004 |
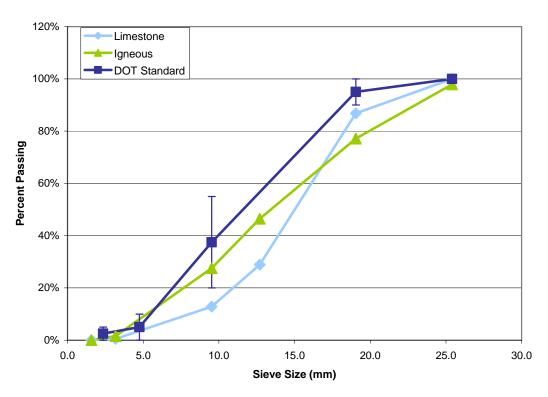
**Plastic Concrete Properties**
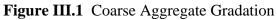
| Concept | Reference |
|---|---|
| Slag cement concrete has lower heat of hydration and improved workability compared to OPC concrete. | Roy and Idorn, 1982<br><br>Meusel and Rose, 1983 |

**Strength**

| Concept | Reference |
|---|---|
| Slag cement concrete has improved late age strength compared to OPC concrete. | Lim and Wee, 2000<br><br>Meusel and Rose, 1983<br><br>Hogan and Meusel, 1981 |
| Slag cement concrete has slow early strength development compared to OPC concrete. | Hogan and Meusel, 1981 |
| The tensile strength of concrete can be predicted based on the compressive strength at the same age. | Oluokun, 1991 |
| There is some evidence that slag cement concrete has an increased tensile-compressive ratio compared to OPC concrete, especially at high replacement levels. | Desai, 2004<br><br>Wainwright and Tolloczko, 1986 |
| Angularity and surface roughness of the coarse aggregate increase the concrete strength. | Soroka, 1980 |

**Appendix III  Material Data**



**Figure III.1**  Coarse Aggregate Gradation
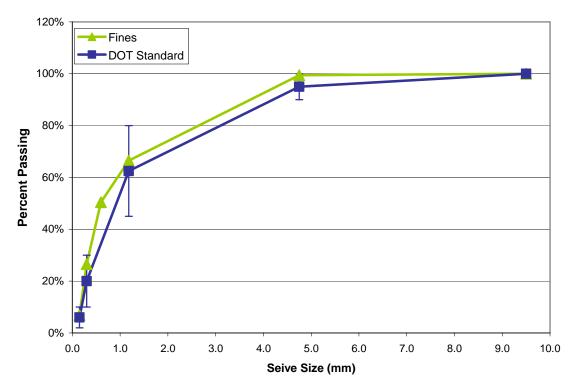


**Figure III.2**  Fine Aggregate Gradation

**Table III.1** Cementitious Material Compositions and Blaine Fineness Values

| | Cement A | Cement B | Cement C | Cement D | Grade 120 Slag Cement |
|---|---|---|---|---|---|
| $SiO_2$ | 19.43 | 19.23 | 19.45 | 20.36 | 20.36 |
| $Al_2O_3$ | 5.04 | 4.52 | 5.32 | 4.79 | 4.79 |
| $TiO_2$ | 0.26 | 0.21 | 0.26 | 0.26 | 0.26 |
| $Fe_2O_3$ | 3.57 | 3.09 | 2.23 | 2.69 | 2.69 |
| CaO | 64.68 | 61.8 | 61.97 | 64.9 | 64.9 |
| MgO | 1.38 | 3.79 | 4.05 | 2.34 | 2.34 |
| $Na_2O$ | 0.28 | 0.17 | 0.21 | 0.15 | 0.15 |
| $K_2O$ | 0.33 | 1.52 | 0.94 | 0.59 | 0.59 |
| $Mn_2O_3$ | 0.02 | 0.04 | 0.11 | | 0.3 |
| $SO_3$ | 3.29 | 4.32 | 3.37 | 2.49 | 2.49 |
| $C_3S$ | 67.3 | 58.34 | 55.92 | 66.34 | -- |
| $C_2S$ | 4.94 | 11.12 | 13.58 | 8.32 | -- |
| $C_3A$ | 7.32 | 6.75 | 10.32 | 8.14 | -- |
| $C_4AF$ | 10.86 | 9.4 | 6.79 | 8.19 | -- |
| Blaine Fineness | 358 | 393 | 336 | 354 | 508 |

# Appendix IV   Hardened Air Void Analysis Results

**Table IV.1.**  Hardened Air Void Analysis Results – Cement A

|  | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
|  | **0%** | **30%** | **50%** | **0%** | **30%** | **50%** |
| **Air Void Content (%)** | 5.2 | 5.9 | 3.8 | 5.9 | 4.9 | 4.6 |
| **Entrained, % ≤ 0.040 in** | 4.1 | 4.5 | 3.5 | 5.3 | 4.3 | 4.0 |
| **Entrained, % > 0.040 in** | 1.1 | 0.4 | 0.3 | 0.6 | 0.6 | 0.6 |
| **Air Voids/inch** | 14.22 | 16.40 | 13.20 | 16.38 | 13.84 | 13.01 |
| **Specific Surface (in$^2$/in$^3$)** | 1090 | 1100 | 1380 | 1120 | 1160 | 1150 |
| **Spacing Factor (in)** | 0.004 | 0.004 | 0.003 | 0.004 | 0.004 | 0.004 |
| **Paste Content (% est.)** | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 |

**Table IV.2.**  Hardened Air Void Analysis Results – Cement B

|  | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
|  | **0%** | **30%** | **50%** | **0%** | **30%** | **50%** |
| **Air Void Content (%)** | 5.3 | 4.2 | 4.1 | 5.8 | 5.7 | 4.7 |
| **Entrained, % ≤ 0.040 in** | 3.5 | 3.7 | 3.3 | 4.7 | 4.2 | 3.5 |
| **Entrained, % > 0.040 in** | 1.5 | 0.5 | 0.8 | 1.1 | 1.5 | 1.2 |
| **Air Voids/inch** | 10.55 | 10.90 | 9.23 | 12.78 | 11.20 | 10.25 |
| **Specific Surface (in$^2$/in$^3$)** | 790 | 1040 | 900 | 880 | 780 | 860 |
| **Spacing Factor (in)** | 0.006 | 0.005 | 0.006 | 0.005 | 0.006 | 0.006 |
| **Paste Content (% est.)** | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 |

**Table IV.3.**  Hardened Air Void Analysis Results – Cement C

|  | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
|  | **0%** | **30%** | **50%** | **0%** | **30%** | **50%** |
| **Air Void Content (%)** | 3.5 | 4.4 | 4.5 | 6.4 | 4.5 | 5.8 |
| **Entrained, % ≤ 0.040 in** | 3.2 | 3.9 | 3.7 | 5.0 | 3.6 | 4.4 |
| **Entrained, % > 0.040 in** | 0.3 | 0.5 | 0.8 | 1.4 | 0.9 | 1.4 |
| **Air Voids/inch** | 10.14 | 12.45 | 10.53 | 13.14 | 10.47 | 12.42 |
| **Specific Surface (in$^2$/in$^3$)** | 1180 | 1130 | 940 | 830 | 930 | 860 |
| **Spacing Factor (in)** | 0.005 | 0.004 | 0.005 | 0.005 | 0.005 | 0.005 |
| **Paste Content (% est.)** | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 |

**Table IV.4.** Hardened Air Void Analysis Results – Cement D

| | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| | **0%** | **30%** | **50%** | **0%** | **30%** | **50%** |
| **Air Void Content (%)** | 6.3 | 4.5 | 4.0 | 7.5 | 6.7 | 5.9 |
| **Entrained, % ≤ 0.040 in** | 5.0 | 4.4 | 3.5 | 6.5 | 6.3 | 5.6 |
| **Entrained, % > 0.040 in** | 1.3 | 0.1 | 0.5 | 1.0 | 0.4 | 0.3 |
| **Air Voids/inch** | 16.30 | 15.91 | 14.02 | 22.38 | 22.37 | 19.01 |
| **Specific Surface (in$^2$/in$^3$)** | 1030 | 1420 | 1420 | 1190 | 1340 | 1290 |
| **Spacing Factor (in)** | 0.004 | 0.004 | 0.004 | 0.003 | 0.003 | 0.003 |
| **Paste Content (% est.)** | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 |

**Table IV.5.** Hardened Air Void Analysis Results – Cement D, 40°F

| | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| | **0%** | **30%** | **50%** | **0%** | **30%** | **50%** |
| **Air Void Content (%)** | 5.6 | 6.6 | 5.2 | 7.6 | 6.0 | 8.9 |
| **Entrained, % ≤ 0.040 in** | 3.9 | 5.4 | 3.9 | 7.0 | 5.2 | 4.9 |
| **Entrained, % > 0.040 in** | 1.7 | 1.2 | 1.3 | 0.6 | 0.8 | 4.0 |
| **Air Voids/inch** | 10.92 | 16.22 | 13.19 | 19.13 | 14.49 | 13.56 |
| **Specific Surface (in$^2$/in$^3$)** | 780 | 990 | 1020 | 1000 | 970 | 610 |
| **Spacing Factor (in)** | 0.006 | 0.004 | 0.005 | 0.004 | 0.004 | 0.006 |
| **Paste Content (% est.)** | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 |

**Appendix V** Compressive Strength Results

**Table V.1.** Compressive Strength Values (psi), Unadjusted for Air – Cement A

| Age | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
| 3 | 3842 | 2910 | 2288 | 2808 | 2240 | 1962 |
| 7 | 4420 | 3736 | 3316 | 3236 | 2906 | 2860 |
| 14 | 4940 | 4735 | 4510 | 3540 | 3656 | 3564 |
| 28 | 5324 | 5362 | 5416 | 3964 | 4282 | 4058 |
| 56 | 5544 | 6048 | 6104 | 4472 | 4816 | 4820 |
| 365 | 6694 | 6774 | 6408 | 5316 | 5344 | 5390 |

**Table V.2.** Compressive Strength Values (psi), Unadjusted for Air – Cement B

| Age | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
| 3 | 4108 | 3400 | 2634 | 3396 | 2984 | 2512 |
| 7 | 4562 | 4080 | 3900 | 3820 | 3512 | 3382 |
| 14 | 4856 | 4694 | 4932 | 4232 | 3838 | 3962 |
| 28 | 5188 | 4992 | 5524 | 4396 | 4398 | 4410 |
| 56 | 5340 | 5434 | 5856 | 4788 | 4784 | 5002 |
| 365 | 6394 | 6416 | 6546 | 5654 | 5424 | 5632 |

**Table V.3.** Compressive Strength Values (psi), Unadjusted for Air – Cement C

| Age | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
| 3 | 3518 | 2996 | 2172 | 2874 | 2452 | 2078 |
| 7 | 4048 | 3930 | 3414 | 3224 | 3402 | 3034 |
| 14 | 4586 | 4604 | 4440 | 3762 | 4012 | 3710 |
| 28 | 5014 | 5384 | 4900 | 3962 | 4560 | 4120 |
| 56 | 5120 | 5644 | 5376 | 4488 | 5204 | 4662 |
| 365 | 5998 | 6204 | 5878 | 5028 | 5610 | 5150 |

**Table V.4.** Compressive Strength Values (psi), Unadjusted for Air – Cement D

| Age | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
| 3 | 3552 | 2990 | 2506 | 2842 | 2168 | 1944 |
| 7 | 4288 | 3994 | 3668 | 3262 | 3104 | 2808 |
| 14 | 4732 | 4718 | 4798 | 3746 | 3602 | 3700 |
| 28 | 5206 | 5618 | 5266 | 4026 | 4026 | 4224 |
| 56 | 5580 | 5928 | 5946 | 4746 | 4452 | 4990 |
| 365 | 6096 | 6504 | 6504 | 5372 | 5078 | 5524 |

**Table V.5.** Compressive Strength Values (psi), Unadjusted for Air – Cement D, 40°F

| Age (Days) | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| | **0%** | **30%** | **50%** | **0%** | **30%** | **50%** |
| 3 | 1826 | 1186 | 786 | 1688 | 1222 | 714 |
| 7 | 3408 | 2270 | 1703 | 2846 | 2278 | 2238 |
| 14 | 4926 | 3292 | 2924 | 3738 | 3240 | 2724 |
| 28 | 5850 | 4182 | 4396 | 4298 | 3920 | 3708 |
| 56 | 6188 | 5220 | 5318 | 4680 | 4786 | 4476 |

**Table V.6.** Compressive Strength Values (psi), Adjusted for Air – Cement A

| Age (Days) | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| | **0%** | **30%** | **50%** | **0%** | **30%** | **50%** |
| 3 | 3710 | 2974 | 2240 | 2912 | 2256 | 1921 |
| 7 | 4268 | 3818 | 3246 | 3356 | 2927 | 2800 |
| 14 | 4770 | 4839 | 4415 | 3671 | 3682 | 3489 |
| 28 | 5140 | 5479 | 5302 | 4111 | 4313 | 3973 |
| 56 | 5353 | 6180 | 5976 | 4638 | 4851 | 4719 |
| 365 | 6463 | 6922 | 6274 | 5513 | 5382 | 5277 |

**Table V.7.** Compressive Strength Values (psi), Adjusted for Air – Cement B

| Age (Days) | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| | **0%** | **30%** | **50%** | **0%** | **30%** | **50%** |
| 3 | 3966 | 3526 | 2561 | 3396 | 3005 | 2459 |
| 7 | 4405 | 4231 | 3792 | 3820 | 3537 | 3311 |
| 14 | 4689 | 4868 | 4795 | 4232 | 3866 | 3879 |
| 28 | 5009 | 5177 | 5371 | 4396 | 4430 | 4317 |
| 56 | 5156 | 5635 | 5693 | 4788 | 4818 | 4897 |
| 365 | 6174 | 6654 | 6364 | 5654 | 5463 | 5514 |

**Table V.8.** Compressive Strength Values (psi), Adjusted for Air – Cement C

| Age (Days) | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| | **0%** | **30%** | **50%** | **0%** | **30%** | **50%** |
| 3 | 3397 | 2913 | 2157 | 2980 | 2367 | 2093 |
| 7 | 3908 | 3821 | 3390 | 3343 | 3285 | 3056 |
| 14 | 4428 | 4476 | 4409 | 3901 | 3874 | 3737 |
| 28 | 4841 | 5234 | 4865 | 4109 | 4403 | 4150 |
| 56 | 4943 | 5487 | 5338 | 4654 | 5025 | 4696 |
| 365 | 5791 | 6032 | 5836 | 5214 | 5417 | 5187 |

**Table V.9.** Compressive Strength Values (psi), Adjusted for Air – Cement D

| Age | Limestone | | | Igneous | | |
|-----|-----|-----|-----|-----|-----|-----|
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
| 3 | 3578 | 3012 | 2453 | 2926 | 2248 | 1987 |
| 7 | 4319 | 4023 | 3591 | 3358 | 3219 | 2869 |
| 14 | 4766 | 4752 | 4697 | 3856 | 3735 | 3781 |
| 28 | 5243 | 5658 | 5156 | 4144 | 4175 | 4316 |
| 56 | 5620 | 5971 | 5821 | 4886 | 4617 | 5099 |
| 365 | 6140 | 6551 | 6368 | 5530 | 5266 | 5645 |

**Table V.10.** Compressive Strength Values (psi), Adjusted for Air – Cement D, 40°F

| Age | Limestone | | | Igneous | | |
|-----|-----|-----|-----|-----|-----|-----|
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
| 3 | 1763 | 1277 | 759 | 1804 | 1240 | 714 |
| 7 | 3290 | 2445 | 1644 | 3042 | 2311 | 2238 |
| 14 | 4756 | 3545 | 2823 | 3995 | 3287 | 2724 |
| 28 | 5648 | 4504 | 4244 | 4593 | 3977 | 3708 |
| 56 | 5975 | 5622 | 5135 | 5002 | 4855 | 4476 |

**Appendix VI**  Split-Tensile Strength Results

**Table VI.1.**  Tensile Strength Values (psi) – Cement A

| Age | Limestone | | | Igneous | | |
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
|---|---|---|---|---|---|---|
| 3 | 384 | 321 | 275 | 327 | 264 | 247 |
| 7 | 437 | 443 | 383 | 359 | 341 | 301 |
| 14 | 424 | 464 | 424 | 373 | 362 | 366 |
| 28 | 485 | 548 | 449 | 395 | 424 | 374 |
| 56 | 543 | 557 | 591 | 430 | 492 | 470 |
| 365 | 654 | 598 | 574 | 509 | 519 | 479 |

**Table VI.2.**  Tensile Strength Values (psi) – Cement B

| Age | Limestone | | | Igneous | | |
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
|---|---|---|---|---|---|---|
| 3 | 463 | 412 | 316 | 350 | 343 | 299 |
| 7 | 453 | 464 | 421 | 374 | 410 | 400 |
| 14 | 460 | 522 | 511 | 389 | 403 | 417 |
| 28 | 466 | 500 | 491 | 433 | 445 | 433 |
| 56 | 458 | 526 | 528 | 463 | 453 | 472 |
| 365 | 548 | 598 | 611 | 495 | 484 | 521 |

**Table VI.3.**  Tensile Strength Values (psi) – Cement C

| Age | Limestone | | | Igneous | | |
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
|---|---|---|---|---|---|---|
| 3 | 368 | 336 | 297 | 336 | 267 | 256 |
| 7 | 440 | 466 | 380 | 362 | 360 | 323 |
| 14 | 443 | 431 | 484 | 384 | 415 | 391 |
| 28 | 502 | 448 | 545 | 432 | 438 | 428 |
| 56 | 462 | 566 | 550 | 451 | 501 | 439 |
| 365 | 577 | 670 | 539 | 489 | 500 | 480 |

**Table VI.4.**  Tensile Strength Values (psi) – Cement D

| Age | Limestone | | | Igneous | | |
| (Days) | 0% | 30% | 50% | 0% | 30% | 50% |
|---|---|---|---|---|---|---|
| 3 | 315 | 315 | 291 | 334 | 279 | 217 |
| 7 | 454 | 393 | 422 | 369 | 353 | 358 |
| 14 | 441 | 455 | 431 | 392 | 381 | 380 |
| 28 | 519 | 510 | 534 | 424 | 416 | 437 |
| 56 | 466 | 565 | 582 | 448 | 454 | 461 |
| 365 | 576 | 606 | 556 | 450 | 501 | 511 |

**Table VI.5.** Tensile Strength Values (psi) – Cement D, 40°F

| Age (Days) | Limestone | | | Igneous | | |
|---|---|---|---|---|---|---|
| | 0% | 30% | 50% | 0% | 30% | 50% |
| 3 | 244 | 160 | 124 | 211 | 195 | 96 |
| 7 | 377 | 304 | 245 | 361 | 280 | 212 |
| 14 | 476 | 404 | 356 | 448 | 378 | 329 |
| 28 | 509 | 487 | 437 | 490 | 418 | 396 |
| 56 | 571 | 578 | 497 | 486 | 485 | 448 |

## A)  Visual Ratings

**Table VII.1**  Visual Rating Key (ASTM C989)

| Rating | Surface Condition |
|---|---|
| 0 | No Scaling |
| 1 | Very light scaling (3mm depth max; no coarse agg. visible) |
| 2 | Slight to moderate scaling |
| 3 | Moderate scaling (some coarse agg. visible) |
| 4 | Moderate to severe scaling |
| 5 | Severe scaling (coarse agg. visible over entire surface) |

**Table VII.2**  Visual Rating – Cement A, Limestone (3-block average)

| Slag Cement Replacement | Curing Method | Freeze-Thaw Cycle | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| 0% | Air | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | SL | | | | | Not applicable for this sequence | | | | | | | | |
| | Pla | | | | | Not applicable for this sequence | | | | | | | | |
| | Wet | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | Wax | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.7 | 1 | 1 | 1 | 1 | 1 |
| | AMS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| 30% | Air | 0 | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | SL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Pla | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Wet | 0 | 1 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Wax | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 3 |
| | AMS | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 50% | Air | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | SL | 0 | 0 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.7 | 0.7 | 1 | 1 |
| | Pla | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Wet | 0 | 1 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Wax | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1.3 | 2 | 2 |
| | AMS | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

**Table VII.3** Visual Rating – Cement C, Limestone (3-block average)

| Slag Cement Replacement | Curing Method | Freeze-Thaw Cycle | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| **0%** | **Air** | 0 | 1.3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **SL** | | | | | Not applicable for this sequence | | | | | | | | |
| | **Pla** | | | | | Not applicable for this sequence | | | | | | | | |
| | **Wet** | 0 | 1.3 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **Wax** | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **AMS** | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **30%** | **Air** | 0 | 1 | 2 | 2.3 | 2.3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | **SL** | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **Pla** | 0 | 0 | 0 | 0.3 | 0.7 | 0.7 | 1 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| | **Wet** | 0 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | **Wax** | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **AMS** | 0 | 1 | 1 | 1 | 1 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| **50%** | **Air** | 0 | 1 | 2 | 2 | 2.3 | 2.3 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |
| | **SL** | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **Pla** | 0 | 0 | 0.7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **Wet** | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | **Wax** | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| | **AMS** | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

**Table VII.4** Visual Rating – Cement A, Igneous (3-block average)

| Slag Cement Replacement | Curing Method | Freeze-Thaw Cycle | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| 0% | Air | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.3 |
| | SL | | | | | Not applicable for this sequence | | | | | | | | |
| | Pla | | | | | Not applicable for this sequence | | | | | | | | |
| | Wet | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Wax | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| | AMS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30% | Air | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | SL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Pla | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Wet | 0 | 0 | 0.7 | 0.7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Wax | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | AMS | 0 | 0.3 | 0.3 | 0.3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 50% | Air | 0 | 0 | 1 | 1 | 1.3 | 1.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| | SL | 0 | 0 | 0.3 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| | Pla | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Wet | 0 | 3 | 3.7 | 3.7 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 |
| | Wax | 0 | 0 | 0.7 | 1 | 1 | 1 | 2 | 3 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 |
| | AMS | 0 | 0 | 1 | 1.3 | 1.3 | 1.7 | 1.7 | 2.7 | 3.3 | 4 | 4.3 | 4.3 | 4.3 |

**Table VII.5**  Visual Rating – Cement C, Igneous (3-block average)

| Slag Cement Replacement | Curing Method | Freeze-Thaw Cycle | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| **0%** | **Air** | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| | **SL** | | | | | Not applicable for this sequence | | | | | | | | |
| | **Pla** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **Wet** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **Wax** | 0 | 0 | 0 | 0 | 0.3 | 1.3 | 1.3 | 2 | 2.3 | 3 | 3 | 3 | 3 |
| | **AMS** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **30%** | **Air** | 0 | 0 | 0 | 0 | 0.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| | **SL** | 0 | 0 | 0 | 0.3 | 1 | 1 | 1 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| | **Pla** | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **Wet** | 0 | 0 | 0 | 0 | 0.7 | 0.7 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.7 |
| | **Wax** | 0 | 0.3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1.3 |
| | **AMS** | 0 | 0 | 0.7 | 0.7 | 0.7 | 0.7 | 1 | 1 | 1 | 1.7 | 1.7 | 1.7 | 1.7 |
| **50%** | **Air** | 0 | 0 | 0.7 | 1 | 1 | 1 | 1 | 1 | 1 | 1.3 | 1.3 | 2.3 | 2.3 |
| | **SL** | 0 | 0 | 0 | 0.3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | **Pla** | 0 | 0 | 0.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| | **Wet** | 0 | 0.3 | 1 | 1 | 1 | 1 | 1 | 1 | 1.3 | 1.7 | 1.7 | 2 | 2 |
| | **Wax** | 0 | 0 | 0.3 | 0.3 | 0.3 | 0.7 | 0.7 | 1 | 1 | 1 | 1 | 1 | 1.3 |
| | **AMS** | 0 | 1 | 1 | 1 | 1 | 1.3 | 1.3 | 2 | 2 | 2 | 2 | 2 | 2 |

**B)  Cumulative Scaling Loss (g/m$^2$)**

**Table VII.6** Cumulative Scaling Loss – Cement A, Limestone (g/m$^2$)

| Slag Cement | Curing Method | Specimen Number | Freeze-Thaw Cycle | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| 0% | Air | 1 | 0 | 12.2 | 13.4 | 14.6 | 14.6 | 14.8 | 15.3 | 15.5 | 15.7 | 15.7 | 16.2 | 16.2 | 16.4 |
| | | 2 | 0 | 5.7 | 7.8 | 8.4 | 9.1 | 9.3 | 9.8 | 9.8 | 10.0 | 10.0 | 10.3 | 10.3 | 10.5 |
| | | 3 | 0 | 3.4 | 3.6 | 5.4 | 5.8 | 8.4 | 8.6 | 8.6 | 8.8 | 8.8 | 9.0 | 9.0 | 9.7 |
| | SL | 1 2 3 | Not applicable for this sequence | | | | | | | | | | | | |
| | Pla | 1 2 3 | Not applicable for this sequence | | | | | | | | | | | | |
| | Wet | 1 | 0 | 13.4 | 16.2 | 18.5 | 18.7 | 20.7 | 22.1 | 23.0 | 23.5 | 23.5 | 24.2 | 24.2 | 24.6 |
| | | 2 | 0 | 10.6 | 14.5 | 17.1 | 17.3 | 20.2 | 21.2 | 22.7 | 23.8 | 23.8 | 23.8 | 23.8 | 24.0 |
| | | 3 | 0 | 8.0 | 10.9 | 13.2 | 13.4 | 15.5 | 17.1 | 17.5 | 18.0 | 18.0 | 18.7 | 18.7 | 19.1 |
| | Wax | 1 | 0 | 2.6 | 2.8 | 3.1 | 3.1 | 4.9 | 5.9 | 5.9 | 6.8 | 6.8 | 7.3 | 7.3 | 8.7 |
| | | 2 | 0 | 0.2 | 1.4 | 3.6 | 12.8 | 17.1 | 20.0 | 26.4 | 26.4 | 33.7 | 33.7 | 38.5 | 38.5 |
| | | 3 | 0 | 0.2 | 1.5 | 1.9 | 9.4 | 11.2 | 25.1 | 29.4 | 29.4 | 34.3 | 34.3 | 37.1 | 37.1 |
| | AMS | 1 | 0 | 0.0 | 0.7 | 2.6 | 3.5 | 6.6 | 10.3 | 13.9 | 20.0 | 20.0 | 20.2 | 20.2 | 21.6 |
| | | 2 | 0 | 0.0 | 0.8 | 2.3 | 2.5 | 4.3 | 7.5 | 13.8 | 28.8 | 28.8 | 29.0 | 29.0 | 31.0 |
| | | 3 | 0 | 0.5 | 1.2 | 2.6 | 3.8 | 6.1 | 8.5 | 10.1 | 16.0 | 16.0 | 16.7 | 16.7 | 17.6 |
| 30% | Air | 1 | 0 | 2.7 | 5.3 | 6.4 | 9.9 | 13.9 | 16.3 | 20.3 | 21.6 | 22.1 | 22.9 | 22.9 | 23.5 |
| | | 2 | 0 | 3.3 | 5.5 | 6.2 | 7.3 | 10.4 | 11.9 | 13.9 | 15.5 | 15.9 | 16.1 | 16.1 | 16.6 |
| | | 3 | 0 | 2.3 | 4.4 | 5.0 | 6.5 | 7.7 | 8.8 | 9.6 | 11.0 | 11.5 | 12.7 | 12.7 | 13.8 |
| | SL | 1 | 0 | 0.4 | 4.0 | 5.1 | 6.1 | 7.3 | 8.9 | 9.1 | 9.3 | 9.3 | 9.5 | 9.5 | 9.9 |
| | | 2 | 0 | 0.7 | 4.1 | 5.3 | 6.5 | 7.3 | 9.0 | 9.4 | 10.2 | 10.2 | 10.4 | 10.4 | 11.1 |
| | | 3 | 0 | 0.4 | 2.1 | 3.0 | 3.9 | 4.7 | 6.0 | 6.4 | 7.1 | 7.1 | 7.1 | 7.1 | 7.7 |
| | Pla | 1 | 0 | 2.3 | 3.4 | 4.8 | 5.5 | 6.2 | 6.4 | 6.6 | 7.1 | 7.1 | 7.3 | 7.3 | 7.5 |
| | | 2 | 0 | 2.2 | 3.3 | 3.5 | 3.8 | 4.4 | 4.6 | 4.9 | 5.1 | 5.1 | 5.7 | 5.7 | 6.2 |
| | | 3 | 0 | 1.9 | 2.8 | 3.5 | 4.0 | 4.7 | 5.2 | 5.4 | 5.6 | 5.6 | 5.6 | 5.6 | 5.6 |
| | Wet | 1 | 0 | 35.8 | 51.3 | 61.3 | 69.8 | 77.3 | 84.4 | 87.7 | 90.0 | 92.9 | 94.8 | 94.8 | 95.2 |
| | | 2 | 0 | 18.8 | 30.8 | 37.1 | 44.6 | 51.9 | 57.5 | 60.6 | 62.9 | 63.8 | 64.2 | 64.2 | 64.4 |
| | | 3 | 0 | 21.2 | 35.6 | 42.2 | 52.2 | 57.5 | 60.3 | 64.1 | 67.2 | 69.0 | 69.8 | 69.8 | 70.1 |
| | Wax | 1 | 0 | 0.2 | 0.4 | 33.3 | 52.4 | 96.9 | 119 | 129 | 134 | 137 | 139 | 139 | 143 |
| | | 2 | 0 | 0.2 | 2.5 | 151 | 181 | 216 | 260 | 271 | 280 | 292 | 295 | 295 | 299 |
| | | 3 | 0 | 0.2 | 14.8 | 50.2 | 195 | 245 | 295 | 381 | 412 | 443 | 477 | 477 | 647 |
| | AMS | 1 | 0 | 0.6 | 7.7 | 9.8 | 17.3 | 18.8 | 20.0 | 21.7 | 22.3 | 23.0 | 23.0 | 23.0 | 23.2 |
| | | 2 | 0 | 0.6 | 5.0 | 5.8 | 8.6 | 10.9 | 12.1 | 12.7 | 12.7 | 13.2 | 13.2 | 13.2 | 13.4 |
| | | 3 | 0 | 0.2 | 7.1 | 13.3 | 20.6 | 23.6 | 25.1 | 26.2 | 27.5 | 27.7 | 28.3 | 28.3 | 31.1 |
| 50% | Air | 1 | 0 | 3.6 | 24.5 | 33.9 | 35.8 | 36.4 | 37.2 | 39.1 | 39.7 | 40.5 | 41.1 | 41.1 | 41.3 |
| | | 2 | 0 | 1.8 | 92.9 | 98.4 | 101 | 102 | 103 | 105 | 106 | 108 | 110 | 110 | 111 |
| | | 3 | 0 | 1.6 | 50.9 | 54.0 | 56.3 | 57.4 | 58.1 | 59.4 | 61.0 | 62.3 | 62.8 | 62.8 | 65.4 |
| | SL | 1 | 0 | 3.0 | 18.8 | 23.0 | 25.0 | 26.0 | 29.5 | 32.8 | 33.5 | 33.8 | 34.5 | 34.5 | 35.5 |
| | | 2 | 0 | 0.9 | 4.6 | 7.5 | 9.1 | 9.1 | 10.7 | 13.0 | 18.0 | 19.6 | 21.4 | 21.4 | 23.9 |
| | | 3 | 0 | 1.2 | 4.1 | 6.1 | 10.7 | 11.6 | 12.4 | 12.8 | 13.1 | 13.8 | 15.8 | 15.8 | 17.9 |
| | Pla | 1 | 0 | 3.5 | 5.3 | 5.5 | 6.0 | 6.0 | 6.3 | 6.3 | 6.3 | 6.3 | 6.3 | 6.3 | 7.0 |
| | | 2 | 0 | 2.0 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.5 | 2.8 | 2.8 | 3.0 |
| | | 3 | 0 | 1.6 | 2.7 | 2.7 | 4.0 | 4.0 | 4.3 | 4.5 | 4.8 | 4.8 | 4.8 | 4.8 | 5.1 |
| | Wet | 1 | 0 | 16.5 | 114 | 126 | 132 | 135 | 138 | 144 | 152 | 157 | 158 | 158 | 160 |
| | | 2 | 0 | 30.2 | 277 | 298 | 309 | 317 | 321 | 325 | 329 | 335 | 338 | 339 | 340 |
| | | 3 | 0 | 6.9 | 105 | 122 | 131 | 138 | 143 | 151 | 161 | 174 | 175 | 176 | 176 |
| | Wax | 1 | 0 | 0.9 | 8.9 | 16.4 | 21.8 | 26.1 | 28.4 | 34.5 | 38.0 | 56.1 | 70.2 | 87.8 | 99.8 |
| | | 2 | 0 | 1.6 | 17.3 | 23.3 | 28.4 | 32.8 | 35.4 | 41.9 | 47.3 | 65.1 | 91.5 | 122 | 145 |
| | | 3 | 0 | 3.4 | 49.9 | 67.6 | 73.0 | 87.5 | 89.9 | 94.1 | 97.7 | 105 | 119 | 127 | 133 |
| | AMS | 1 | 0 | 1.0 | 14.8 | 17.7 | 20.1 | 20.8 | 20.8 | 21.1 | 22.0 | 22.0 | 22.0 | 22.3 | 24.5 |
| | | 2 | 0 | 0.5 | 19.1 | 24.1 | 25.7 | 26.4 | 26.4 | 26.6 | 26.6 | 26.9 | 27.1 | 27.1 | 27.1 |
| | | 3 | 0 | 2.1 | 6.5 | 10.3 | 12.4 | 13.2 | 13.2 | 14.0 | 14.0 | 14.0 | 14.2 | 14.2 | 14.5 |

**Table VII.7** Cumulative Scaling Loss – Cement C, Limestone (g/m$^2$)

| Slag Cement | Curing Method | Specimen Number | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | **Freeze-Thaw Cycle** | | | | | | | |
| 0% | Air | 1 | 0 | 55.7 | 71.2 | 73.4 | 74.8 | 76.8 | 77.7 | 77.7 | 77.7 | 77.7 | 78.0 | 78.0 | 82.1 |
| | | 2 | 0 | 42.1 | 68.5 | 72.4 | 74.4 | 74.8 | 77.3 | 77.5 | 77.5 | 77.5 | 77.7 | 77.7 | 81.1 |
| | | 3 | 0 | 43.3 | 60.3 | 63.3 | 64.5 | 66.3 | 67.5 | 67.5 | 67.5 | 67.5 | 67.8 | 67.8 | 69.0 |
| | SL | 1 2 3 | | | | | | Not applicable for this sequence | | | | | | | |
| | Pla | 1 2 3 | | | | | | Not applicable for this sequence | | | | | | | |
| | Wet | 1 | 0 | 30.6 | 38.6 | 42.6 | 44.3 | 45.6 | 47.1 | 47.1 | 47.1 | 47.1 | 47.1 | 47.1 | 47.1 |
| | | 2 | 0 | 23.8 | 37.7 | 43.4 | 46.2 | 48.3 | 50.1 | 50.1 | 50.1 | 50.1 | 50.4 | 50.4 | 51.4 |
| | | 3 | 0 | 51.4 | 70.5 | 79.0 | 83.2 | 85.6 | 89.9 | 90.9 | 90.9 | 90.9 | 92.1 | 92.1 | 92.4 |
| | Wax | 1 | 0 | 8.0 | 12.4 | 14.8 | 18.4 | 19.9 | 25.9 | 29.6 | 31.3 | 31.3 | 34.2 | 34.2 | 44.1 |
| | | 2 | 0 | 8.2 | 13.6 | 18.8 | 21.1 | 22.8 | 25.6 | 27.0 | 27.7 | 27.7 | 29.4 | 29.4 | 32.2 |
| | | 3 | 0 | 7.8 | 17.6 | 22.8 | 24.2 | 25.6 | 27.0 | 28.2 | 28.4 | 28.4 | 28.7 | 28.7 | 33.6 |
| | AMS | 1 | 0 | 16.0 | 24.2 | 28.3 | 33.4 | 36.3 | 40.2 | 41.4 | 42.6 | 42.6 | 43.6 | 43.6 | 46.7 |
| | | 2 | 0 | 14.5 | 20.0 | 22.5 | 23.8 | 24.0 | 25.5 | 25.5 | 25.5 | 25.5 | 25.8 | 25.8 | 28.3 |
| | | 3 | 0 | 21.8 | 31.5 | 37.5 | 40.9 | 42.1 | 44.8 | 46.3 | 46.3 | 46.3 | 46.3 | 46.3 | 46.7 |
| 30% | Air | 1 | 0 | 50.6 | 134 | 165 | 173 | 183 | 197 | 199 | 208 | 217 | 217 | 220 | 221 |
| | | 2 | 0 | 54.9 | 133 | 175 | 188 | 190 | 191 | 192 | 193 | 194 | 194 | 195 | 197 |
| | | 3 | 0 | 45.7 | 96.3 | 176 | 223 | 242 | 248 | 251 | 254 | 255 | 255 | 257 | 261 |
| | SL | 1 | 0 | 4.4 | 9.3 | 12.1 | 14.5 | 14.5 | 18.6 | 18.6 | 18.6 | 18.6 | 19.4 | 19.4 | 19.6 |
| | | 2 | 0 | 5.9 | 9.8 | 11.9 | 16.3 | 17.1 | 21.4 | 22.0 | 22.2 | 22.5 | 22.5 | 22.5 | 23.5 |
| | | 3 | 0 | 5.1 | 7.5 | 8.4 | 13.7 | 15.1 | 24.8 | 26.4 | 27.0 | 27.7 | 28.1 | 28.1 | 28.8 |
| | Pla | 1 | 0 | 4.8 | 7.0 | 8.5 | 12.8 | 13.1 | 17.4 | 17.7 | 17.9 | 17.9 | 18.2 | 18.2 | 18.2 |
| | | 2 | 0 | 10.4 | 31.8 | 38.2 | 58.0 | 64.4 | 101 | 104 | 106 | 106 | 106 | 106 | 110 |
| | | 3 | 0 | 0.3 | 0.6 | 6.1 | 23.7 | 26.5 | 58.1 | 60.3 | 62.0 | 62.6 | 62.8 | 62.8 | 63.4 |
| | Wet | 1 | 0 | 237 | 275 | 286 | 290 | 292 | 294 | 296 | 298 | 301 | 301 | 304 | 306 |
| | | 2 | 0 | 221 | 265 | 282 | 286 | 288 | 290 | 292 | 294 | 297 | 297 | 300 | 302 |
| | | 3 | 0 | 173 | 194 | 205 | 210 | 214 | 215 | 216 | 217 | 219 | 219 | 220 | 223 |
| | Wax | 1 | 0 | 22.3 | 48.8 | 93.9 | 123 | 128 | 131 | 133 | 136 | 139 | 139 | 142 | 145 |
| | | 2 | 0 | 15.0 | 28.2 | 66.2 | 98.4 | 106 | 109 | 112 | 115 | 117 | 117 | 119 | 121 |
| | | 3 | 0 | 7.3 | 26.4 | 72.5 | 116 | 125 | 128 | 130 | 138 | 142 | 142 | 144 | 147 |
| | AMS | 1 | 0 | 23.0 | 29.4 | 33.8 | 35.6 | 36.9 | 38.0 | 38.9 | 41.3 | 42.4 | 42.4 | 44.6 | 45.5 |
| | | 2 | 0 | 35.8 | 47.3 | 58.1 | 68.1 | 73.4 | 77.6 | 80.0 | 82.4 | 84.4 | 84.4 | 87.8 | 90.6 |
| | | 3 | 0 | 61.9 | 74.0 | 92.2 | 115 | 130 | 138 | 141 | 146 | 148 | 148 | 158 | 160 |
| 50% | Air | 1 | 0 | 83.8 | 221 | 290 | 329 | 341 | 348 | 354 | 359 | 363 | 365 | 369 | 371 |
| | | 2 | 0 | 54.0 | 143 | 195 | 211 | 221 | 225 | 230 | 237 | 247 | 253 | 257 | 261 |
| | | 3 | 0 | 81.9 | 131 | 189 | 220 | 225 | 241 | 255 | 259 | 264 | 273 | 283 | 290 |
| | SL | 1 | 0 | 0.0 | 17.0 | 29.1 | 31.8 | 35.4 | 37.6 | 39.8 | 41.2 | 45.6 | 47.5 | 47.5 | 49.0 |
| | | 2 | 0 | 4.2 | 27.7 | 51.2 | 54.5 | 57.5 | 63.4 | 67.4 | 70.7 | 74.9 | 76.6 | 76.6 | 80.6 |
| | | 3 | 0 | 0.5 | 4.6 | 18.7 | 21.6 | 23.2 | 29.8 | 32.3 | 35.3 | 37.3 | 38.0 | 38.0 | 38.3 |
| | Pla | 1 | 0 | 6.8 | 31.2 | 35.9 | 40.9 | 42.7 | 43.9 | 45.1 | 47.0 | 47.0 | 47.9 | 47.9 | 50.0 |
| | | 2 | 0 | 2.1 | 6.1 | 13.1 | 15.7 | 18.4 | 19.2 | 20.3 | 20.5 | 21.6 | 22.4 | 22.4 | 23.5 |
| | | 3 | 0 | 3.8 | 12.1 | 15.8 | 29.8 | 32.2 | 33.0 | 33.5 | 33.8 | 34.1 | 34.4 | 34.4 | 34.4 |
| | Wet | 1 | 0 | 103 | 147 | 191 | 202 | 205 | 208 | 210 | 216 | 219 | 221 | 225 | 228 |
| | | 2 | 0 | 175 | 224 | 233 | 237 | 244 | 245 | 247 | 249 | 253 | 255 | 260 | 264 |
| | | 3 | 0 | 147 | 180 | 200 | 213 | 220 | 224 | 226 | 228 | 230 | 231 | 232 | 233 |
| | Wax | 1 | 0 | 12.3 | 36.3 | 90.9 | 108 | 116 | 119 | 120 | 150 | 166 | 170 | 172 | 177 |
| | | 2 | 0 | 5.7 | 27.6 | 91.2 | 124 | 131 | 136 | 144 | 150 | 154 | 158 | 163 | 166 |
| | | 3 | 0 | 11.4 | 40.3 | 149 | 194 | 217 | 225 | 236 | 242 | 246 | 252 | 256 | 259 |
| | AMS | 1 | 0 | 26.5 | 59.4 | 85.0 | 92.8 | 109 | 120 | 131 | 146 | 159 | 164 | 169 | 175 |
| | | 2 | 0 | 58.1 | 92.1 | 137 | 146 | 163 | 169 | 177 | 180 | 186 | 189 | 192 | 198 |
| | | 3 | 0 | 24.1 | 48.7 | 66.5 | 70.6 | 74.9 | 78.1 | 80.7 | 82.2 | 86.1 | 90.8 | 99.0 | 102 |

**Table VII.8** Cumulative Scaling Loss – Cement A, Igneous (g/m$^2$)

| Slag Cement | Curing Method | Specimen Number | Freeze-Thaw Cycle | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| 0% | Air | 1 | 0 | 2.8 | 5.8 | 5.8 | 6.0 | 7.3 | 7.3 | 7.3 | 7.5 | 7.5 | 7.5 | 18.0 | 20.4 |
| | | 2 | 0 | 3.8 | 11.3 | 13.0 | 14.1 | 14.1 | 14.4 | 15.7 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 |
| | | 3 | 0 | 7.1 | 8.4 | 8.7 | 8.7 | 8.9 | 8.9 | 8.9 | 8.9 | 9.1 | 9.1 | 9.1 | 9.1 |
| | SL | 1 2 3 | Not applicable for this sequence | | | | | | | | | | | | |
| | Pla | 1 2 3 | Not applicable for this sequence | | | | | | | | | | | | |
| | Wet | 1 | 0 | 1.7 | 3.0 | 3.2 | 3.2 | 3.4 | 3.7 | 3.7 | 3.9 | 4.1 | 4.1 | 4.1 | 4.1 |
| | | 2 | 0 | 1.9 | 2.9 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 4.1 | 4.4 | 4.4 | 4.4 | 4.4 |
| | | 3 | 0 | 2.8 | 5.9 | 6.2 | 6.2 | 6.5 | 6.7 | 6.7 | 7.0 | 7.0 | 7.0 | 7.5 | 7.5 |
| | Wax | 1 | 0 | 0.7 | 0.7 | 0.9 | 0.9 | 1.3 | 1.3 | 1.3 | 1.5 | 1.5 | 1.5 | 4.6 | 8.0 |
| | | 2 | 0 | 2.0 | 5.9 | 6.6 | 8.4 | 9.8 | 13.4 | 21.2 | 27.3 | 39.6 | 39.6 | 62.4 | 84.9 |
| | | 3 | 0 | 0.7 | 1.0 | 1.2 | 1.9 | 3.4 | 8.7 | 17.9 | 31.5 | 47.5 | 47.5 | 61.5 | 82.1 |
| | AMS | 1 | 0 | 0.0 | 0.3 | 0.5 | 1.0 | 1.8 | 5.7 | 6.7 | 10.6 | 11.4 | 11.4 | 13.0 | 13.0 |
| | | 2 | 0 | 0.0 | 0.2 | 1.0 | 1.7 | 2.7 | 7.5 | 8.7 | 13.8 | 14.5 | 14.5 | 15.5 | 15.5 |
| | | 3 | 0 | 0.5 | 0.9 | 1.4 | 1.8 | 2.7 | 5.0 | 5.0 | 6.4 | 6.4 | 6.4 | 6.6 | 6.6 |
| 30% | Air | 1 | 0 | 3.1 | 3.6 | 3.9 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 5.8 |
| | | 2 | 0 | 5.5 | 8.3 | 8.5 | 9.3 | 9.3 | 9.3 | 9.8 | 10.0 | 10.0 | 10.3 | 10.3 | 11.3 |
| | | 3 | 0 | 4.4 | 5.1 | 5.1 | 5.1 | 5.1 | 5.3 | 5.3 | 5.6 | 5.6 | 6.3 | 6.3 | 7.8 |
| | SL | 1 | 0 | 1.9 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 |
| | | 2 | 0 | 1.2 | 1.9 | 1.9 | 2.9 | 2.9 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 |
| | | 3 | 0 | 2.1 | 4.4 | 4.4 | 4.7 | 4.9 | 5.4 | 5.7 | 5.9 | 5.9 | 5.9 | 5.9 | 5.9 |
| | Pla | 1 | 0 | 0.3 | 0.3 | 0.3 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| | | 2 | 0 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.9 |
| | | 3 | 0 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| | Wet | 1 | 0 | 14.5 | 20.6 | 31.2 | 40.0 | 40.5 | 42.6 | 59.6 | 61.2 | 64.3 | 65.8 | 65.8 | 68.6 |
| | | 2 | 0 | 6.8 | 11.3 | 19.1 | 27.3 | 28.2 | 28.5 | 39.8 | 40.5 | 42.6 | 43.3 | 43.3 | 46.1 |
| | | 3 | 0 | 1.7 | 4.4 | 7.8 | 10.2 | 10.4 | 14.8 | 31.5 | 32.9 | 34.1 | 34.4 | 34.4 | 37.8 |
| | Wax | 1 | 0 | 3.9 | 37.1 | 48.4 | 63.0 | 75.1 | 83.6 | 97.6 | 101 | 105 | 109 | 109 | 117 |
| | | 2 | 0 | 9.0 | 22.0 | 35.4 | 58.6 | 69.2 | 75.2 | 82.2 | 85.8 | 86.3 | 88.6 | 88.6 | 93.3 |
| | | 3 | 0 | 4.1 | 49.5 | 71.3 | 78.8 | 88.7 | 91.2 | 93.8 | 94.3 | 95.3 | 96.2 | 96.2 | 101 |
| | AMS | 1 | 0 | 4.6 | 14.3 | 20.4 | 22.8 | 24.0 | 25.2 | 26.4 | 26.7 | 27.2 | 27.6 | 27.6 | 33.7 |
| | | 2 | 0 | 11.9 | 23.3 | 30.2 | 32.7 | 34.1 | 35.9 | 38.2 | 38.6 | 38.9 | 40.9 | 40.9 | 47.1 |
| | | 3 | 0 | 3.9 | 10.7 | 14.3 | 17.2 | 17.9 | 18.7 | 19.6 | 20.8 | 22.3 | 23.3 | 23.3 | 27.6 |
| 50% | Air | 1 | 0 | 11.3 | 23.0 | 28.7 | 45.1 | 58.0 | 68.1 | 93.7 | 96.5 | 97.5 | 99.8 | 100 | 101 |
| | | 2 | 0 | 6.4 | 12.9 | 16.0 | 26.6 | 35.3 | 44.9 | 59.3 | 62.4 | 63.5 | 65.2 | 67.3 | 68.5 |
| | | 3 | 0 | 3.4 | 18.9 | 41.2 | 77.3 | 97.8 | 133 | 205 | 213 | 216 | 223 | 227 | 232 |
| | SL | 1 | 0 | 1.0 | 5.2 | 6.2 | 6.2 | 6.4 | 6.9 | 6.9 | 6.9 | 7.2 | 7.2 | 7.4 | 7.4 |
| | | 2 | 0 | 0.0 | 6.3 | 13.5 | 23.1 | 25.4 | 33.6 | 39.7 | 49.3 | 51.0 | 51.0 | 54.8 | 58.1 |
| | | 3 | 0 | 0.0 | 3.2 | 6.7 | 7.2 | 7.2 | 7.5 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 | 7.7 |
| | Pla | 1 | 0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.3 | 1.3 | 2.1 | 3.1 |
| | | 2 | 0 | 1.1 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 2.6 |
| | | 3 | 0 | 1.5 | 1.8 | 3.0 | 3.8 | 3.8 | 4.1 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 |
| | Wet | 1 | 0 | 158 | 214 | 236 | 276 | 292 | 307 | 344 | 355 | 362 | 374 | 378 | 388 |
| | | 2 | 0 | 189 | 269 | 314 | 356 | 367 | 380 | 394 | 404 | 413 | 433 | 445 | 459 |
| | | 3 | 0 | 305 | 375 | 389 | 434 | 455 | 480 | 545 | 572 | 611 | 689 | 731 | 902 |
| | Wax | 1 | 0 | 2.3 | 15.8 | 42.6 | 69.5 | 105 | 121 | 227 | 284 | 301 | 341 | 353 | 372 |
| | | 2 | 0 | 12.8 | 44.0 | 81.8 | 97.0 | 125 | 132 | 185 | 203 | 213 | 219 | 220 | 223 |
| | | 3 | 0 | 14.8 | 46.0 | 91.3 | 99.8 | 107 | 111 | 135 | 142 | 151 | 176 | 183 | 195 |
| | AMS | 1 | 0 | 10.4 | 30.0 | 44.1 | 63.5 | 90.1 | 101 | 251 | 306 | 335 | 371 | 385 | 391 |
| | | 2 | 0 | 10.0 | 26.3 | 36.6 | 40.6 | 46.3 | 49.6 | 112 | 156 | 174 | 197 | 198 | 200 |
| | | 3 | 0 | 6.5 | 42.1 | 68.8 | 105 | 189 | 218 | 382 | 411 | 425 | 433 | 438 | 446 |

**Table VII.9** Cumulative Scaling Loss – Cement C, Igneous (g/m$^2$)

| Slag Cement | Curing Method | Specimen Number | Freeze-Thaw Cycle | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| 0% | Air | 1 | 0 | 1.7 | 1.7 | 3.3 | 5.5 | 10.2 | 10.7 | 12.4 | 13.2 | 13.2 | 15.2 | 15.2 | 15.4 |
| | | 2 | 0 | 1.8 | 1.8 | 2.5 | 2.8 | 7.3 | 10.8 | 20.0 | 21.0 | 21.0 | 22.0 | 22.0 | 24.3 |
| | | 3 | 0 | 2.5 | 2.5 | 5.3 | 7.5 | 18.5 | 24.8 | 32.0 | 34.0 | 34.0 | 34.5 | 34.5 | 35.0 |
| | SL | 1 2 3 | Not applicable for this sequence | | | | | | | | | | | | |
| | Pla | 1 | 0 | 0.7 | 0.7 | 0.7 | 0.7 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| | | 2 | 0 | 0.2 | 0.2 | 0.2 | 0.2 | 1.5 | 1.5 | 1.5 | 2.2 | 2.2 | 2.2 | 2.2 | 2.7 |
| | | 3 | 0 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| | Wet | 1 | 0 | 0.6 | 0.6 | 1.1 | 1.1 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 2.0 |
| | | 2 | 0 | 1.1 | 1.1 | 6.4 | 13.9 | 15.0 | 15.2 | 15.5 | 15.8 | 15.8 | 15.8 | 15.8 | 16.0 |
| | | 3 | 0 | 0.3 | 0.3 | 0.5 | 1.6 | 1.9 | 2.1 | 2.1 | 2.7 | 2.7 | 3.5 | 3.5 | 4.5 |
| | Wax | 1 | 0 | 2.1 | 2.1 | 23.9 | 70.9 | 148 | 180 | 263 | 337 | 390 | 442 | 442 | 511 |
| | | 2 | 0 | 0.7 | 0.7 | 10.2 | 28.5 | 60.1 | 74.0 | 112 | 151 | 188 | 225 | 225 | 300 |
| | | 3 | 0 | 1.3 | 1.3 | 10.7 | 21.2 | 32.5 | 41.1 | 66.0 | 87.5 | 108 | 129 | 129 | 161 |
| | AMS | 1 | 0 | 2.1 | 2.1 | 11.6 | 18.1 | 22.2 | 23.8 | 27.6 | 28.4 | 28.4 | 29.5 | 29.5 | 30.5 |
| | | 2 | 0 | 2.4 | 2.4 | 8.9 | 10.6 | 12.2 | 13.2 | 16.2 | 16.5 | 16.5 | 18.8 | 18.8 | 20.0 |
| | | 3 | 0 | 2.8 | 2.8 | 8.5 | 11.8 | 14.1 | 14.9 | 18.2 | 19.6 | 19.6 | 20.4 | 20.4 | 22.3 |
| 30% | Air | 1 | 0 | 2.2 | 2.7 | 7.0 | 13.1 | 39.3 | 46.8 | 50.4 | 58.4 | 66.2 | 73.5 | 73.5 | 77.3 |
| | | 2 | 0 | 1.9 | 5.3 | 6.5 | 50.4 | 97.6 | 105 | 108 | 109 | 111 | 113 | 113 | 116 |
| | | 3 | 0 | 0.9 | 5.5 | 7.1 | 8.2 | 12.5 | 15.9 | 19.1 | 20.3 | 23.2 | 24.6 | 24.6 | 28.9 |
| | SL | 1 | 0 | 0.7 | 4.8 | 16.7 | 55.0 | 70.7 | 77.0 | 87.4 | 87.4 | 89.4 | 90.6 | 90.6 | 98.1 |
| | | 2 | 0 | 0.0 | 5.2 | 16.3 | 64.2 | 73.3 | 95.9 | 124 | 124 | 131 | 136 | 136 | 142 |
| | | 3 | 0 | 0.5 | 14.0 | 64.6 | 77.5 | 81.9 | 89.4 | 93.3 | 93.3 | 95.3 | 99.2 | 99.2 | 105 |
| | Pla | 1 | 0 | 3.3 | 21.0 | 35.9 | 55.7 | 64.9 | 69.3 | 75.3 | 75.3 | 77.3 | 78.8 | 78.8 | 81.8 |
| | | 2 | 0 | 2.1 | 13.6 | 28.8 | 41.1 | 47.7 | 54.4 | 66.1 | 66.1 | 69.6 | 70.1 | 70.1 | 70.9 |
| | | 3 | 0 | 0.3 | 2.9 | 5.1 | 6.9 | 7.4 | 8.0 | 8.6 | 8.6 | 8.6 | 8.6 | 8.6 | 8.6 |
| | Wet | 1 | 0 | 1.2 | 9.7 | 14.8 | 22.0 | 38.8 | 41.9 | 43.6 | 47.5 | 50.9 | 51.6 | 51.6 | 54.7 |
| | | 2 | 0 | 2.9 | 4.8 | 7.0 | 66.1 | 72.2 | 83.1 | 84.8 | 86.2 | 86.5 | 86.7 | 86.7 | 106 |
| | | 3 | 0 | 3.2 | 5.6 | 7.3 | 12.4 | 17.9 | 31.5 | 33.0 | 33.5 | 33.7 | 35.4 | 35.4 | 37.3 |
| | Wax | 1 | 0 | 29.3 | 134 | 169 | 202 | 220 | 231 | 245 | 248 | 251 | 259 | 259 | 263 |
| | | 2 | 0 | 17.8 | 91.8 | 111 | 133 | 140 | 144 | 166 | 168 | 170 | 170 | 170 | 172 |
| | | 3 | 0 | 18.7 | 75.2 | 81.7 | 94.3 | 97.2 | 99.4 | 119 | 120 | 121 | 122 | 122 | 137 |
| | AMS | 1 | 0 | 6.2 | 16.9 | 22.4 | 32.9 | 39.3 | 41.6 | 42.5 | 43.9 | 48.7 | 53.9 | 53.9 | 57.4 |
| | | 2 | 0 | 3.9 | 27.6 | 35.8 | 43.1 | 49.5 | 75.4 | 77.5 | 80.5 | 81.6 | 81.6 | 81.6 | 82.7 |
| | | 3 | 0 | 6.1 | 41.4 | 58.4 | 79.4 | 87.9 | 95.2 | 98.1 | 103 | 107 | 108 | 108 | 109 |
| 50% | Air | 1 | 0 | 2.5 | 8.3 | 13.6 | 19.7 | 36.3 | 36.8 | 37.9 | 44.8 | 50.7 | 58.4 | 63.7 | 64.5 |
| | | 2 | 0 | 10.2 | 54.5 | 104 | 119 | 127 | 133 | 155 | 158 | 159 | 171 | 179 | 201 |
| | | 3 | 0 | 3.7 | 27.7 | 34.7 | 42.1 | 50.1 | 54.9 | 58.7 | 58.7 | 58.9 | 60.8 | 62.4 | 63.5 |
| | SL | 1 | 0 | 0.0 | 1.9 | 25.3 | 53.9 | 59.5 | 68.8 | 71.5 | 73.1 | 75.7 | 75.7 | 77.1 | 78.7 |
| | | 2 | 0 | 0.0 | 0.5 | 19.4 | 34.1 | 35.4 | 36.4 | 38.0 | 40.8 | 42.1 | 42.1 | 42.1 | 43.4 |
| | | 3 | 0 | 0.0 | 1.7 | 27.9 | 52.4 | 56.0 | 57.4 | 59.6 | 61.0 | 61.2 | 61.2 | 62.3 | 65.1 |
| | Pla | 1 | 0 | 1.3 | 30.7 | 107 | 121 | 122 | 123 | 124 | 124 | 124 | 124 | 124 | 124 |
| | | 2 | 0 | 3.0 | 34.2 | 104 | 118 | 121 | 123 | 125 | 126 | 128 | 128 | 130 | 133 |
| | | 3 | 0 | 1.7 | 14.8 | 50.5 | 56.2 | 56.4 | 56.7 | 56.7 | 56.7 | 56.7 | 56.7 | 56.7 | 56.7 |
| | Wet | 1 | 0 | 37.8 | 72.3 | 100 | 107 | 116 | 123 | 125 | 132 | 140 | 141 | 142 | 144 |
| | | 2 | 0 | 17.2 | 33.8 | 41.3 | 41.3 | 42.1 | 46.4 | 52.9 | 59.3 | 78.4 | 80.0 | 82.9 | 82.9 |
| | | 3 | 0 | 6.1 | 33.2 | 45.7 | 49.8 | 73.3 | 81.7 | 91.3 | 97.2 | 103 | 105 | 105 | 105 |
| | Wax | 1 | 0 | 10.2 | 19.5 | 26.2 | 27.5 | 34.7 | 37.7 | 43.8 | 47.8 | 49.4 | 50.2 | 50.2 | 57.2 |
| | | 2 | 0 | 17.1 | 31.2 | 40.3 | 46.3 | 57.9 | 67.3 | 74.5 | 78.9 | 83.0 | 89.4 | 94.3 | 102 |
| | | 3 | 0 | 27.9 | 80.5 | 101 | 111 | 118 | 119 | 127 | 129 | 130 | 131 | 134 | 151 |
| | AMS | 1 | 0 | 173 | 221 | 238 | 249 | 255 | 255 | 255 | 266 | 275 | 277 | 285 | 299 |
| | | 2 | 0 | 123 | 166 | 179 | 201 | 220 | 225 | 229 | 237 | 242 | 249 | 249 | 253 |
| | | 3 | 0 | 155 | 206 | 227 | 232 | 281 | 292 | 314 | 331 | 336 | 337 | 337 | 344 |

**Appendix VIII**  Carbonation Test Results

**Table VIII.1**  Carbonation Depths at 14 Days (mm)

| Mix Properties | | | Air | Soda Lime | Plastic Wrap | Wet | Wax | AMS |
|---|---|---|---|---|---|---|---|---|
| Cement A | 0% | Limestone | 0 | -- | -- | 0 | 0 | 0 |
| | | Igneous | 0.2 | -- | -- | 0.5 | 0 | 0 |
| | 30% | Limestone | 0 | ^ | ^ | 0 | 0 | 0 |
| | | Igneous | 0.3 | ^ | ^ | 0.4 | 0 | 0 |
| | 50% | Limestone | 0 | ^ | ^ | 0 | 0 | 0 |
| | | Igneous | 0.2 | ^ | ^ | 0.4 | 0.3* | 0 |
| Cement C | 0% | Limestone | 0 | -- | -- | 0 | 0 | 0 |
| | | Igneous | 0 | -- | ^ | 0.5 | 0 | 0 |
| | 30% | Limestone | 1.25 | ^ | ^ | 1.0 | 0 | 0.5 |
| | | Igneous | 0.6 | ^ | ^ | 0.8 | 0 | 0 |
| | 50% | Limestone | 0 | ^ | ^ | 0 | 0 | 0 |
| | | Igneous | 0.5 | ^ | ^ | 0.5 | 0 | 0 |

\* Denotes carbonation that only occurred in some areas along tested cross section.

^ Specimens were not tested at 14 days because curing materials were not removed until 28 days.

**Table VIII.2**  Carbonation Depths at 28 Days (mm)

| Mix Properties | | | Air | Soda Lime | Plastic Wrap | Wet | Wax | AMS |
|---|---|---|---|---|---|---|---|---|
| Cement A | 0% | Limestone | 0 | -- | -- | 0.5 | 0 | 0 |
| | | Igneous | 0 | -- | -- | 0.4 | 0 | 0 |
| | 30% | Limestone | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Igneous | 2.0 | 0 | 0 | 0.4 | 0 | 0 |
| | 50% | Limestone | 0 | 0.4* | 0 | 0 | 0 | 0 |
| | | Igneous | 1.0 | 1.7 | 0 | 0.5 | 0 | 0 |
| Cement C | 0% | Limestone | 0.5 | -- | -- | 0.9 | 0 | 0 |
| | | Igneous | 1.6 | -- | 0.2 | 0.8 | 0 | 0 |
| | 30% | Limestone | 1.0 | 0.2 | 0 | 0.6 | 0 | 0.4 |
| | | Igneous | 2.6 | 0 | 0 | 0.7 | 0 | 0 |
| | 50% | Limestone | 0.3 | 0.3* | 0 | 0.6 | 0 | 0.1 |
| | | Igneous | 2.9 | 0 | 0 | 1.3 | 0 | 0 |

\* Denotes carbonation that only occurred in some areas along tested cross section.

**Table VIII.3** Carbonation Depths at 40 Days (mm)

| Mix Properties | | | Air | Soda Lime | Plastic Wrap | Wet | Wax | AMS |
|---|---|---|---|---|---|---|---|---|
| **Cement A** | **0%** | **Limestone** | 0 | -- | -- | 0.5 | 0 | 0 |
| | | **Igneous** | 0 | -- | -- | 0.5 | 0 | 0 |
| | **30%** | **Limestone** | 0.5 | 0 | 0 | 0.5 | 0 | 0 |
| | | **Igneous** | 0.5 | 0 | 0 | 1.1 | 0 | 0 |
| | **50%** | **Limestone** | 0 | 0 | 0 | 0.2 | 0 | 0 |
| | | **Igneous** | 1.5 | 0 | 0 | 1.6 | 0 | 0 |
| **Cement C** | **0%** | **Limestone** | 0 | -- | -- | 1.0 | 0 | 0.8 |
| | | **Igneous** | 0.4 | -- | 0.2 | 0.6 | 0 | 0 |
| | **30%** | **Limestone** | 1.0 | 0.4 | 0 | 0.6 | 0 | 0.2 |
| | | **Igneous** | 1.8 | 1.0 | 0 | 0.9 | 0 | 0 |
| | **50%** | **Limestone** | 0.6 | 0.4 | 0.2 | 0.6 | 0 | 0.4* |
| | | **Igneous** | 3.5 | 0.3 | 0.3 | 1.3 | 0 | 0 |

* Denotes carbonation that only occurred in some areas along tested cross section.


**Table VIII.4** Carbonation Depths at 60 Days (mm)

| Mix Properties | | | Air | Soda Lime | Plastic Wrap | Wet | Wax | AMS |
|---|---|---|---|---|---|---|---|---|
| **Cement A** | **0%** | **Limestone** | 0.3 | -- | -- | 0.4 | 0 | 0 |
| | | **Igneous** | 2.0* | -- | -- | 0.5 | 0 | 0 |
| | **30%** | **Limestone** | 1.25 | 0.2* | 0 | 0.5 | 0 | 0.2 |
| | | **Igneous** | 3.0 | 3.0 | 1.0 | 1.0 | 0 | 0 |
| | **50%** | **Limestone** | 0.4 | 0.2 | 0.2 | 0.3 | 0 | 0 |
| | | **Igneous** | 4.8 | 3.5 | 1.1 | 1.9 | 3.5 | 0 |
| **Cement C** | **0%** | **Limestone** | 0.3 | -- | -- | 0.7 | 0.3 | 0.3 |
| | | **Igneous** | 2.4 | -- | 0 | 0.8 | 0 | 0 |
| | **30%** | **Limestone** | 0.4 | 0 | 0.2 | 0.5 | 0 | 0.4 |
| | | **Igneous** | 3.0 | 1.0 | 0.4 | 1.7 | 0 | 0 |
| | **50%** | **Limestone** | 0.3 | 0.4 | 0.2 | 0.6 | 0 | 0.4* |
| | | **Igneous** | 3.1 | 1.3 | 0.6 | 2.0 | 0 | 3.3* |

* Denotes carbonation that only occurred in some areas along tested cross section.

**Table VIII.5**  Carbonation Depths at 80 Days (mm)

| Mix Properties | | | Air | Soda Lime | Plastic Wrap | Wet | Wax | AMS |
|---|---|---|---|---|---|---|---|---|
| Cement A | 0% | Limestone | 0.5 | -- | -- | 0.8 | 0 | 0 |
| | | Igneous | 3.4 | -- | -- | 1.8 | 0 | 2.8 |
| | 30% | Limestone | 1.75 | 0.6 | 0.6 | 0.8 | 0 | 0.2 |
| | | Igneous | 3.1 | 2.8 | 2.0 | 1.2 | 0 | 0 |
| | 50% | Limestone | 0.2 | 1.5 | 2.0 | 0.3 | 0 | 0 |
| | | Igneous | 5.9 | 3.9 | 1.1 | 2.3 | 4.6 | 0 |
| Cement C | 0% | Limestone | 0.2 | -- | -- | 0.7 | 0 | 0 |
| | | Igneous | 1.6 | -- | 0.3 | 1.2 | 0 | 0 |
| | 30% | Limestone | 0.3 | 0.3 | 0.2 | 0.8 | 0 | 0.4 |
| | | Igneous | 2.9 | 1.8 | 1.0 | 1.7 | 0 | 0 |
| | 50% | Limestone | 0.5 | 1.0 | 2.0 | 1.3 | 0 | 0.3 |
| | | Igneous | 4.5 | 3.8 | 1.6 | 2.7 | 0 | 0 |