Application of Self-Consolidating Concrete in Bridge Structures

Final Report

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EXECUTIVE SUMMARY

The objectives of this research were to evaluate the feasibility and performance of self-consolidating concrete (SCC) made with local aggregates for use in cast-in-place and precast concrete applications and to develop draft specifications, acceptance criteria, mix qualifications, and guidelines for use of SCC by SDDOT. Box culverts were designated as the first type of structures be constructed by SDDOT using SCC.

A study was conducted at South Dakota State University to determine the feasibility of constructing precast and cast-in-place box culverts in South Dakota using SCC made with local aggregates. The research included literature search and review, development of SCC mix designs utilizing South Dakota local aggregates, aggregate testing, material testing of both fresh and hardened SCC properties, development of SCC special provisions in coordination with SDDOT staff and industry representatives, and evaluation of constructability of SCC box culverts.

Twelve SCC mixes were studied. The parameters were aggregate type, water/cement ratio, and mixing duration. The mixes were developed for two types of coarse aggregates: two-stage crushed quartzite (eastern South Dakota) and crushed limestone (western South Dakota). Two mixing durations were utilized to simulate precast and cast-in-place applications. In all, four application types were considered in this study to represent precast and cast-in-place applications using either western South Dakota or eastern South Dakota aggregates. For each application type, three w/c ratios, 0.38, 0.42, and 0.46, were investigated. The w/c ratio was varied by simultaneous adjustment of the water and the cement quantities to maintain the same mix yield volume under different w/c ratios. The ratio of the high range water reducing admixture (HRWRA) to the cement was maintained the same within the same mix type. Therefore, the amount of HRWRA was decreased as the w/c ratio was increased.

Fresh concrete tests were performed on the SCC to evaluate flowability, passing ability, and segregation resistance. Hardened concrete tests were performed to measure compressive strength, tensile strength, modulus of rupture, and segregation.

In addition to the laboratory work described in this report, the project included on-site construction observation and field inspection after one winter in service of conventional concrete and SCC box culverts. Four box culverts (one precast and three cast-in-place culverts) were built partially with SCC. All four structures were located along Highway 44 in Rapid City, SD.

As part of this research, special provisions for the use of SCC in box culverts in South Dakota were developed. The special provisions were a collaborative effort between the researchers at SDSU, SDDOT, and members of the concrete industry. The special provisions are presented in Appendix C.
Based on the experimental results, the following conclusions were made.

Plastic SCC Behavior

1. As the w/c ratio increased, the SCC flowability (slump) typically increased.
2. As the w/c ratio increased, the blocking potential typically decreased.
3. As the w/c ratio increased, the T_{20} value decreased.
4. As the w/c ratio increased, the L-Box H2/H1 ratio typically increased.
5. As the w/c ratio increased, the air content of the precast mixes (short-duration mixing) decreased while the air content of the cast-in-place mixes remained practically unchanged.

Hardened SCC Behavior

6. As the w/c ratio increased, the SCC compressive strength decreased.
7. The 7-day compressive strength values were compared to the 28-day compressive strength values. Results indicated that the strength development rate of SCC is comparable to that of conventional concrete.
8. As the w/c ratio increased, the splitting tensile strength decreased. The results also indicated that the relationship between the splitting tensile strength and the compressive strength of SCC is comparable to that of conventional concrete.
9. As the w/c ratio increased, the modulus of rupture of the SCC decreased. The results indicated that the relationship between the modulus of rupture and the compressive strength of SCC is comparable to that of conventional concrete and that the ACI empirical equation for determining the modulus of rupture is suitable for use with SCC.

Constructability of SCC Box Culverts

10. The major precasting plants and concrete batch plants in South Dakota are well equipped to successfully produce SCC for precast and cast-in-place highway structures.
11. According to industry representatives, the production cost of SCC was 20% to 65% higher than that of conventional concrete.
12. Casting SCC was significantly faster than casting conventional concrete and required approximately one-quarter to one-third of the labor force needed to cast a similar amount of conventional concrete.
13. The SCC box culverts did not show any signs of early deterioration following one winter in service.

General

14. When properly sized and shaped, South Dakota local aggregates were found to be suitable for producing SCC.
15. All SCC mix designs considered in this study were found stable, under the laboratory conditions, by visual stability index and hardened visual stability index.
16. The highest w/c ratio used (0.46) resulted in the most economical SCC mix (least amounts of cement and HRWRA) and the highest fluidity.
17. The measured SCC 28-day compressive strength varied between 40.5 MPa (5880 psi) and 52.8 MPa (7650 psi). Even at a w/c ratio of 0.46, the concrete strength was adequate for most cast-in-place and precast applications.
18. The measured air content was either within or higher than the limits set by SDDOT for conventional concrete. The air content can be easily modified by adjusting the amount of the air entraining admixture. Allowance for air loss due to pumping should be considered.
19. Except for one of the 12 mixes considered in this study, the measured slump spread values were 500 mm (20 in.) or more. For applications such as single footings or columns that do not require the concrete to flow for a long distance in the formwork, a 500 mm (20 in.) spread appears to be adequate. It is recommended that the slump spread lower limit be set in the SDDOT special provisions for SCC at 500 mm (20 in.). This would allow for greater flexibility and more efficient use of application-based performance measures.
20. For cast-in-place SCC applications where the concrete is expected to remain in the concrete mixer for an extended duration before it is discharged, the HRWRA should be added and mixed on the jobsite immediately before concrete discharge. This will reduce the potential for evaporation of the HRWRA and will ensure adequate slump spread.

Based on the results of this study, the following recommendations are made:

1. The South Dakota Department of Transportation should permit the use of SCC for cast-in-place and precast applications.
2. SDDOT should adopt the special provisions that were developed in this study for the use of SCC for the construction of cast-in-place and pre-cast box culverts. The development of the special provisions was a collaborative effort among the researchers at SDSU, SDDOT, and members of the concrete industry. The special provisions are presented in Appendix C.
3. The concrete producer should be responsible for the design of a SCC mix to meet the client's stated performance levels. The special provisions that were developed in this study set performance levels and acceptance criteria for SCC mixtures when used for the fabrication of cast-in-place and precast box culverts in South Dakota.
4. The SDDOT concrete technicians should be trained to conduct the slump spread (ASTM C 1611) and the J-Ring spread (ASTM C 1621) SCC acceptance tests.
5. The performance of the slump spread and the J-Ring spread tests requires a non-absorbent board and a steel J-Ring apparatus. SDDOT should purchase and maintain an adequate number of non-absorbent boards and J-Ring apparatuses. The purchase cost of such tools is nominal.
6. For cast-in-place SCC applications where the concrete is expected to remain in the concrete mixer for an extended duration before it is discharged, the HRWRA should be added and mixed on the jobsite immediately before concrete discharge. This will reduce the potential for evaporation of the HRWRA and will ensure adequate slump spread.
7. The slump spread lower limit in the proposed special provisions has been set at 560 mm (22 in.). For applications such as single footings or columns that do not require the concrete to flow for a long distance in the formwork, a 500 mm (20 in.) spread appears to be adequate. For such applications, it is recommended that the slump spread lower limit be reduced to 500 mm (20 in.). This would allow for greater flexibility and more efficient use of application-based performance measures.

1. INTRODUCTION

1.1 Problem Description

Self-consolidating concrete (SCC) is a specially proportioned hydraulic cement concrete that enables fresh concrete to flow without segregation. Because of its high workability, SCC flows into narrow spaces and form corners, and around closely-spaced steel reinforcement, without the need for mechanical vibration. While the cost of SCC is slightly higher than that of standard concrete, the use of SCC would result in enhanced finished quality, reduced labor cost, higher productivity, and increased safety as a consequence of the reduced labor force needed to place the concrete (Cameron, 2003).

Because of its favorable properties and ease of handling, SCC is rapidly becoming the material of choice in the production of precast concrete panels used for cladding. The benefits of SCC can be extended to precast and cast-in-place structural elements. However, the use of SCC for structural applications has been limited in the United States because of concerns about certain design and construction issues that may influence the performance and integrity of structural elements. These issues include workability, strength development, aggregate segregation, creep and shrinkage, production, and constructability.

There are many potential applications for SCC in bridge structures. For example, precast and cast-in-place box culverts, precast girders, retaining structures, pile foundations, narrow and thin elements, and other structural elements with heavy reinforcement are a few examples where the use of SCC may be advantageous. Past experience in South Dakota indicates that the construction of narrow-walled box culverts using standard concrete mix designs may result in internal voids and construction defects (see Figure 1.1). The use of SCC may eliminate the occurrence of such defects and may result in better final products.

Figure 1.1 Concrete Void in the Wall of a Cast-In-Place Box Culvert (Courtesy SDDOT)

SCC has gained widespread use in Japan and Europe. The technology has been gaining interest in the United States. Few departments of transportation across the United States have initiated or completed studies to evaluate the feasibility and performance of SCC in bridge structural elements. The South Dakota Department of Transportation (SDDOT) does not allow the use of SCC in its projects. As a result, the precast concrete and concrete production industry in South Dakota may be reluctant to develop SCC production and construction techniques for highway structures.

SCC mix proportions and properties are dependent, among other factors, upon the physical properties of the coarse aggregates used in the mix. Precast and concrete producers normally use limestone aggregates in western South Dakota and quartzite aggregates in eastern South Dakota. SDDOT currently does not have specifications or mix qualification guidelines for the use of SCC. Therefore, SDDOT needs to determine SCC mix designs that are specific to South Dakota.

A planning meeting was organized by SDDOT in Pierre, SD, on February 7, 2006, where researchers from the Department of Civil and Environmental Engineering at South Dakota State University (SDSU) met with the technical panel for this project. It was agreed that a research study was needed to assess the feasibility of SCC use for cast-in-place and precast box culverts, and to develop guidelines for use of SCC by SDDOT.

1.2 Objectives

Proportioning, behavior, and properties of SCC are highly dependent on the coarse aggregates' physical properties. Two types of aggregates, crushed limestone and quartzite, are frequently used in preparing concrete for SDDOT bridges. Therefore, a research study was needed in South Dakota in order to develop draft specifications, acceptance criteria, mix qualifications, and guidelines for use of SCC made with either quartzite or limestone coarse aggregate.

The study covered in this report addressed the following two main objectives.

2. Evaluation of the feasibility and performance of SCC for use in cast-in-place and precast concrete products.
3. Development of draft specifications, acceptance criteria, mix qualifications and guidelines for use of SCC by SDDOT.

1.3 Scope

The research covered in this report included an experimental study of SCC mixtures and field evaluation of precast and cast-in-place box culverts made of SCC and conventional concrete.

Twelve SCC mixes were studied. The parameters were aggregate type, water/cement (w/c) ratio, and mixing duration. The mixes were developed for two types of coarse aggregates: two-stage crushed quartzite (eastern South Dakota) and crushed limestone (western South Dakota). Three w/c ratios, 0.38, 0.42, and 0.46, were investigated. Two mixing durations were utilized to simulate precast and cast-in-place applications.

The original scope required the inspection during construction and after one winter in service of six box culvert structures. The six structures were to represent precast and cast-in-place SCC box culverts in eastern and western South Dakota. Due to the lack of a sufficient number of box culverts planned for construction during the course of this study and other scheduling conflicts, only four box culverts (one precast and three cast-in-place) made partially with SCC were constructed and inspected. All four culverts were located on Highway 44 in western South Dakota and incorporated limestone coarse aggregate.

2. LITERATURE REVIEW

2.1 Introduction

Self-consolidating concrete (SCC) in its fresh state is a workable concrete that flows under its own weight around reinforcement to fill formwork without the need for vibration. There are three characteristics required for a concrete to be classified as self-consolidating are: filling ability, passing ability and segregation resistance (Khayat 2004; PCI 2003). The filling ability is the ability of the concrete to fill the formwork under its own weight. Passing ability is the ability to flow through confined spaces and dense reinforcement without blocking or separation of the mix. Segregation resistance is the ability of the concrete to maintain homogeneity and keep the aggregate in suspension during transport, placement, and after placement.

SCC technology was initially developed in Japan in the 1980s to address the lack of skilled workers and to provide a durable concrete with reduced need for labor during construction. SCC was first successfully used in Japan in 1988. In the 1990s, development and use of SCC technology started in Sweden and then quickly expanded throughout Europe. Specifications and guidelines for SCC use have already been developed in Europe (Goodier 2003; PCI 2003). SCC research and use has recently been making progress in North America and has been of particular interest to concrete producers and users. The American Concrete Institute (ACI), American Society of Testing and Materials (ASTM), and Precast/Prestressed Concrete Institute (PCI) are in the process of standardizing SCC testing and placement. PCI has published “Interim Guidelines for the Use of Self-Consolidating Concrete in PCI Member Plants” (PCI 2003). ASTM published test methods for slump flow, passing ability, and static segregation of SCC (ASTM 2006).

The use of SCC is gaining interest because it has been shown to reduce the need for labor, construction time, and noise associated with vibrating concrete. SCC also provides better quality with fewer occurrences of “bugholes”, bubbles, and honeycombing, resulting in a better finished product and reducing the need for patching and repairing (Bonen 2005; Goodier 2003; Nowak 2005). SCC can fill intricate formwork and can be used to cast geometrically complex members or members with congested reinforcement (PCI 2003). Inadequate compaction of ordinary vibrated concrete can cause entrapped air to develop during concrete placement and air pockets to form around the reinforcing steel bars and in narrow members. Too much vibration can cause the segregation of the concrete, bleeding and loss of air voids (Bonen 2005; Mindess 2003). SCC has little or no need for added vibration. Therefore, problems associated with too much or too little vibration may be avoided. It has been shown that SCC can be designed to match or exceed the strengths of ordinary vibrated concrete (Collepardi 2005). The bond of SCC to steel reinforcement also has been shown to be better than that of ordinary vibrated concrete (Collepardi 2005).

While SCC provides many advantages, its plastic behavior may be very sensitive to variations in properties and amount of its constituent materials. Therefore, greater care must be taken when batching SCC than when batching conventional concrete. Due to the lack of standardization of test methods and placing procedures, using a new technology such as SCC must be done carefully (Goodier 2003). There is also concern that due to a high amount of paste, SCC may be more susceptible to creep and shrinkage (Persson 2005).

2.2 Effects of Constituent Materials on SCC Properties

Self-consolidating concrete is produced in three main types: powder-type, viscosity modifying admixture (VMA)-type, and combination-type. Powder-type SCC has high powder content. The powder may be cement and fillers such as fly ash, limestone powder, slag, and silica fume. High range water reducing (HRWR) admixtures, also called superplasticizers, are used to achieve high flowability. Segregation resistance is achieved by using high powder content, VMA, or a combination of the two (Bonen 2005; Berke 2003). The different ingredients used and their effects on the properties of SCC will be discussed in subsequent sections of this paper.

2.2.1 Aggregates

Aggregates affect many properties of concrete in both the fresh state and hardened state. The shape, size, gradation, porosity, and moisture content of the aggregate are a few of the characteristics that affect the properties of a mix. Standard tests to determine particle size distribution (ASTM C136), density, specific gravity, absorption (ASTM C127 and C128), and unit weight (ASTM C29) were performed on the aggregates used for preparing the SCC mixes in this study.

2.2.1.1 Aggregate Amount

For SCC to flow under its own weight, friction between aggregate particles needs to be reduced. Reduction in friction is achieved by increasing the distance between particles by increasing the amount of paste (Khayat 1999). An increase in the amount of aggregate, especially coarse aggregate, will cause a decrease in workability (Ye 2005). However, more aggregate is generally associated with increase in strength and decrease in creep and shrinkage (Kosmatka 2002). An appropriate amount and type of aggregate must be used to obtain an optimum performance of SCC.

2.2.1.2 Aggregate Shape

The shape of aggregates can vary from rough and angular to smooth and rounded. One study found that less paste volume was required for naturally rounded aggregates than for crushed aggregates, which was attributed to the packing density of the mixes (Proske 2005). Rounded aggregates improve flowability while angular aggregates may result in higher risk for blockage (Pellerin 2005).

2.2.1.3 Aggregate Size

Aggregate size is classified into two categories, fine aggregate and coarse aggregate. Fine aggregates pass the No. 4 sieve, while coarse aggregates do not. Studies have shown that larger aggregates are more prone to segregation (Bonen 2005; Proske 2005). The maximum aggregate size must be chosen so as to avoid blockage. It has been recommended that the coarse aggregate size for SCC be between ⅜″ and ½″, but not to exceed ¾″ (Pellerin 2005). More paste is generally required for smaller aggregate sizes due to larger surface area associated with smaller aggregates. Because cement is the most expensive component of concrete, decreasing the paste content may be desirable (Nowak 2005). Packing density depends on the size, shape, and particle size distribution of aggregates. Packing density affects how much paste is required; a high packing density requires less paste but may increase the risk for blockage (Proske 2005).

2.2.1.4 Aggregate Porosity and Moisture Content

Porosity and moisture content of aggregates affect the amount of water that may be required in a mix, and may influence changes in properties of a mix. Excess water stored in voids of aggregates will cause more water in the mix than desired. Pores in aggregates may absorb water resulting in less water available for reaction in the paste. SCC is more sensitive to changes in water content than conventional concrete (Goodier 2003). Changes in water content cause drastic changes in workability, segregation resistance, and the hardened concrete mechanical properties (Collepardi 2005).

2.2.2 Cement

When producing concrete, cement reacts with water and gains strength in a chemical process called hydration. After hardening, the mass has stone-like properties. Hydration will continue as long as conditions are favorable to the process (sufficient moisture and suitable temperatures). As hydration continues, concrete becomes harder and stronger. Hydration is facilitated by curing, which maintains favorable conditions for the process. Most of the strength gain occurs in the first 28 days of hydration. The compressive strength of the hydrated cement is affected by the cement type which is based on compound composition and fineness of cement (Mindess 2003).

ASTM C 150-05: “Standard Specification for Portland Cement” (ASTM 2006) classifies Portland cement into five main types, Type I, Type II, Type III, Type IV, and Type V. Type I Portland cement is used when special properties of other cements are not necessary. Type II Portland cement is used when moderate sulfate resistance or moderate heat of hydration are desired. Type III Portland cement is used when high early strength is desired. Type IV Portland cement is used when low heat of hydration is desired. Type V Portland cement is used when high sulfate resistance is desired (ASTM 2006). The most commonly used type of Portland cement is Type I (Mindess 2003). The appropriate type of cement should be chosen for each project. Similar to conventional concrete, the water/cement ratio is considered when evaluating the effect of cement on SCC properties (Mindess 2003).

2.2.3 Fillers

Fillers, also called additions or mineral admixtures, are used in addition to or to partially replace some of the cement in a concrete mix. Some examples of fillers include fly ash, ground granulated blast-furnace slag, silica fume, and limestone powder. Fillers may be added to enhance a certain concrete property or to reduce the amount of cement required. Replacing cement with fillers may reduce the cost of the concrete (Mindess 2003). Two common fillers will be discussed in this paper: fly ash and limestone powder.

2.2.3.1 Fly Ash

Fly ash is the most commonly used mineral admixture in concrete. Fly ash is a byproduct of coal combustion. Fly ash will chemically react with calcium hydroxide released during hydration of cement to form cementitious compounds. There are two classes of fly ash commonly used: Class F fly ash and Class C fly ash. The South Dakota Department of Transportation does not allow the use of Class C fly ash for structural concrete (SDDOT 2004). Rheological properties of concrete are influenced by fly ash because of its small particle size and spherical shape. The spherical shape of fly ash particles acts like a lubricant and improves fluidity of SCC, unlike Portland cement particles which have angular shape. Using fly ash reduces water demand and increases workability in both conventional concrete and SCC.

There are several benefits associated with using fly ash as partial replacement for cement. Fly ash use has been associated with reduced water demand, improved workability, improved stability, increased cohesiveness and less bleeding and segregation (Shadle 2003). Fly ash reduces the amount of cement required, resulting in lower concrete material cost and less energy consumption to produce cement (Babu 2005; Shadle 2003). The use of fly ash for concrete eliminates the need to dispose of the fly ash, which is a waste product from coal combustion (Shadle 2003). Using fly ash as filler was shown to improve durability, through increased resistance to freezing and thawing, improved sulfate resistance, decreased permeability, and lower alkali-aggregate reaction (Babu 2005; Mindess 2003). However, fly ash has a lower heat of hydration than Portland cement (Mindess 2003) and will generally retard the setting time of the concrete, causing a decrease in early strength development (Christensen 2005; Mindess 2003). Fly ash may cause a decrease in early strength, but will result in long term high strength (Mindess 2003; Shadle 2003).

One study found that rejected fly ash use may be possible in producing SCC. Rejected fly ash does not meet the requirements for use in concrete because more than 50% of the fly ash particles would have been retained on the 45 µm sieve (Poon 2005). Another study concluded that fly ash is the best overall pozzolanic material for controlling autogenous and drying shrinkage in SCC with high paste volume (Suksawang 2005).

2.2.3.2 Limestone Powder

Limestone powder can be used as a mineral admixture in SCC. Higher dosages of limestone powder were found to improve flowability and increase compressive strength of concrete. The optimum limestone powder dosage was strongly dependent on the type of cement used (Zsigovics 2005). One study found that using limestone filler reduced drying shrinkage and lowered autogenous shrinkage more than fly ash did (Rozière 2005).

2.2.4 Water

The amount of water, or more specifically, the amount of water relative to the amount of cement or cementitious materials, has a major effect on the properties of SCC. Cementitious materials include cement and fillers that partially replace the cement. The effect of water to cement ratio (w/c) and water to cementitious materials ratio (w/cm) in conventional concrete has been established (Mindess 2003).

An adequate amount of water in a concrete mix is required to react with the cement for the mix to gain strength. However, increasing the w/c or w/cm ratio above the amount needed to hydrate the cement causes a decrease in compressive strength and modulus of elasticity of SCC (Issa 2005). An increased w/c ratio improves fluidity of concrete, however, the risk of segregation increases with an increase in the w/c ratio. Conversely, if the w/cm is too low, the concrete will be too viscous and will have reduced flowability. Superplasticizers may be added to enhance flowability (Bonen 2005).

Concrete durability is adversely affected by a higher w/c ratio. An increased w/c ratio will result in (Brunner 2005; Mindess 2003):

- Decreased compressive strength
- Increased autogenous shrinkage
- Increased drying shrinkage and greater crack sensitivity
- Increased water absorption coefficient
- Increased carbonation depth
- Decreased frost resistance
- Increased gas permeability
- Increased chloride diffusion

The amount of water must be determined for each mix to achieve the desired characteristics of concrete. SCC can be very sensitive to variations in water content (Goodier 2003). Therefore, excess water on aggregates, aggregate absorption, and admixture water may need to be considered when determining the amount of water in a mix.

2.2.5 High Range Water Reducers (HRWR)

High-range water reducing (HRWR) admixtures, referred to as superplasticizers, are used to reduce the yield stress of plastic concrete and to make concrete flow more easily without excess water. HRWR admixtures in conventional concrete increase the flowability of concrete at reduced w/c ratio and maintain resistance to bleeding and segregation. However, as the amount of superplasticizer increases, the potential for segregation of the mix increases (Mindess 2003). SCC utilizes a larger amount of superplasticizer than conventional concrete, and therefore, segregation of SCC becomes a concern. Durability characteristics, such as drying shrinkage, chloride permeability, and strength development of concrete with HRWR admixtures are comparable to those of concrete without HRWR admixtures (Collepardi 2005).

Naphthalene sulfonate-based superplasticizers are used in conventional concrete to improve flowability. However, polyether- and polycarboxylate ether-based superplasticizers are normally used for SCC. Polyether- and polycarboxylate ether-based superplasticizers provide better dispersability, minimal setting retardation, and reduced risk of segregation. They also provide high flowability, increased slump and better slump retention (Shonaka 2003). The superplasticizer used in this research was polycarboxylate-based. Recently, studies have developed a new lignosulfonate-based superplasticizer that can be used for SCC (Petersen 2005; Wallevik 2005).

2.2.6 Viscosity Modifying Admixtures (VMA)

Superplasicizers reduce the yield stress and viscosity of concrete, thereby increasing the risk of segregation in SCC. VMAs are used to enhance the viscosity of the mix and control segregation. Superplasticizers and VMAs have opposite effects on concrete. Superplasticizers increase flowability while VMAs decrease flowability (Berke 2003).

VMAs can limit segregation, improve the rheology and cohesion, and improve robustness of an SCC mix. Therefore, the mix becomes much less sensitive to variations in constituent materials, including water content, and placement conditions (Berke 2003; Phyfferoen 2003). A mix that is less sensitive to variability makes production easier and more reliable. Increasing the VMA content decreases the fluidity of the mix. Some VMA types retard the setting time of SCC (Berke 2003).

2.3 Fresh Concrete Properties and Testing

SCC is characterized by its fresh properties – filling ability, passing ability, and segregation resistance. SCC must be able to fill formwork that may be intricate and/or have regions of congested reinforcement under its own weight while retaining stability of the mix. According to PCI, the three properties of SCC are defined as follows (PCI 2003):

> Filling ability – (confined flowability) – The ability of SCC to flow under its own weight (without vibration) into and fill completely all spaces within intricate formwork, containing obstacles, such as reinforcement.
>
> Passing ability – The ability of SCC to flow through openings approaching the size of the mix coarse aggregate, such as the spaces between steel reinforcing bars, without segregation or aggregate blocking.
>
> Stability – (segregation resistance) – The ability of SCC to remain homogeneous during transport, placing, and after placement.

All three characteristics must be met for a concrete to be classified as SCC. These three properties are generally agreed upon in literature.

Stability of SCC includes dynamic stability and static stability. Dynamic stability is required during mixing, placement, flowing through forms and reinforcement and free fall. Static stability is required after placement to prevent settlement of aggregates and bleeding (Daczko 2003).

A project called TESTING-SCC was carried out in Europe to determine which SCC tests were best suited for standardization (Bartos 2005). According to TESTING-SCC, tests for filling ability should be representative of "how far a fresh SCC mix would flow under its own weight, how well it would fill formwork and spaces of varying degrees of complexity and how fast the mix would flow" (Bartos 2005). Test methods that can be used to evaluate the filling ability of an SCC mix are:

- Slump flow test, spread and T500 (or T20)
- Orimet test
- V-funnel test

Tests for passing ability (blocking) should be representative of "how well a fresh SCC mix will flow through constricted spaces and between reinforcement" (Bartos 2005). Blocking may occur due to coarse aggregate wedging between bars or arch action caused by aggregate that is too large, too much aggregate, or segregation. Blocking may also occur when the filling ability becomes so low that it will not pass through congested areas. Test methods that can be used to evaluate passing ability of an SCC mix are:

- L-box test
- J-ring test, spread and step

Segregation resistance tests are best used at the mix design stage. Test methods that can be used to evaluate segregation resistance are:

- column segregation test
- penetration test
- wet sieving (sieve stability segregation test)
- visual stability index (VSI)

Severe segregation can be detected from some of the tests for filling or passing ability (Bartos 2005). The test methods that were performed on concrete mixes for this research project are: slump flow spread test with T500 (T20) and visually stability index, J-ring spread test, L-box test, and column segregation test. These test methods are discussed in detail in Section 5.

2.4 Hardened Concrete Properties and Testing

The hardened properties of SCC are evaluated by compressive strength, modulus of elasticity, tensile strength, shear strength, creep, shrinkage, frost resistance, sulfate resistance, alkali-silicate reactivity, corrosion resistance, carbonation depth, and permeability and diffusion.

Studies by Attiogbe (2003) and Collepardi (2005) concluded that the compressive strength of SCC is comparable or higher than that of conventional concrete of the same w/c ratio. Bonen (2005), Hegger (2005), and Walraven (2005) reported that the modulus of elasticity of SCC is lower than that of conventional concrete of the same compressive strength. Hegger (2005) and Walraven (2005) also reported that the tensile strength of SCC is higher than that for conventional concrete, due to the homogeneous interface between the aggregates and paste. Das (2005) and Hegger (2005) concluded that the shear strength of SCC was similar to or higher than that of ordinary concrete. The shear strength enhancement results from the better microstructure caused by high content of powder materials. Collepardi (2005) reported that SCC has a better bond with reinforcement than ordinary concrete. Daczko (2005) stated that SCC may experience top bar effect, or lesser bond to reinforcement at the top of a member, if the mix does not have adequate segregation resistance.

Reports of creep and shrinkage values of SCC as compared to conventional concrete are conflicting in the literature. Some reported that SCC experiences more shrinkage and creep than ordinary concrete does (Turcry 2003), whereas some reported that creep and shrinkage of SCC are comparable to those of ordinary concrete (Raghavan 2003; Persson 2003). Creep and shrinkage of concrete depend on age at loading, aggregate type and content, maturity, moisture content, porosity, rate of loading, size of specimen, stress to strength level, time of loading, temperature, and water-cement ratio (Kosmatka 2002, Mindess 2003). Creep and shrinkage also depend on the amount of paste in the mix. Higher paste content causes an increase in creep and shrinkage. Therefore, the high paste content of SCC may make it susceptible to more creep and shrinkage. Increasing the w/c ratio will have a negative effect on durability characteristics, such as creep and shrinkage, of the concrete. Extended curing times will reduce these effects (Mindess 2003). Studies have shown that VMA-type SCC will experience less shrinkage than powder-type SCC (Attiogbe 2003). This may be due to the fact that VMA-type SCC has less paste than powder-type SCC.

In one study, the amount of cement was kept constant while the amount of water and the amount of curing time were varied (Brunner 2005). This study found that in SCC with high water content, shrinkage cracking could be reduced by increasing curing time. Another study found that creep and shrinkage were on the same order for SCC and conventional concrete of the same strength (Persson 2005). The similar behavior was attributed to opposite effects. SCC contains less aggregate and more paste volume, causing an increase in creep and shrinkage. SCC had more packing of particles and higher strength due to lower w/c ratio, causing a decrease in creep and shrinkage (Persson 2005). Another study found that ordinary concrete and SCC developed similar total shrinkage but autogenous shrinkage was a larger part of the total shrinkage for SCC than for ordinary concrete (Piérard 2005).

Frost resistance, sulfate resistance, alkali-silicate reactivity, corrosion resistance, carbonation depth, and permeability and diffusion of SCC were generally comparable to those of conventional concrete. This was especially evident with SCC of lower w/c ratios. (Assié 2005; Audenaert 2003; Boel 2005; Brunner 2005) For this research, the hardened concrete tests performed were the same as those that would be used for conventional concrete. The test methods are discussed further in Section 5. The tests that were performed are:

- ASTM C39, “Standard Test Method for Compressive Strength of Cylindrical Concrete Sections,” to determine compressive strength at 7 days and 28 days
- ASTM C78, “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading,” to determine the modulus of rupture at 28 days
- ASTM C496, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens,” to determine the tensile strength at 28 days
- AASHTO draft specification “Static Segregation of Hardened Self-Consolidating Concrete Cylinders”

2.5 Previous Work of Departments of Transportation

Some departments of transportation (DOT) have developed special provisions for the use of SCC in their states. This section presents a summary of some of such special provisions.

2.5.1 North Carolina DOT

Following is a listing of the North Carolina DOT requirements for materials used to produce SCC (North Carolina 2005):

- Cement – Use a minimum of 639 lb/yd^3 and a maximum of 850 lb/yd^3.
- Pozzolan – A pozzolan such as fly ash, ground granulated blast furnace slag, silica fume or limestone powder may be substituted for a portion of the cement.
- Coarse and fine aggregate – Use a fine aggregate content of 40% to 60% of the combined coarse and fine aggregate weight.
- Water – (for precast concrete) Use a quantity of water such that w/cm is no greater than 0.48.
- Admixtures – Use of a VMA is recommended to enhance homogeneity.

The North Carolina DOT requires a slump spread of 24 inches to 30 inches using an inverted cone, a difference in spread between slump flow and J-ring tests not to exceed 2 inches, and, an L-Box ratio of H2/H1 between 0.8 and 1.0 (North Carolina 2005). The North Carolina DOT also requires that concrete delivery be timed such that consecutive lifts will combine without segregation, the time between consecutive lifts not to exceed 20 minutes, the horizontal flow distance not to exceed 30 feet, and the vertical free fall distance not to exceed 10 feet (North Carolina 2005).

2.5.2 Illinois DOT

The Illinois DOT requires that the maximum VSI value be 1, the maximum hardened VSI (HVSI by the cut cylinder method) be 1, the maximum J-ring value be 4 inches, the L-box blocking ratio be a minimum of 60%, and the slump flow be between 20 and 28 inches (Illinois 2005).

2.5.3 Florida DOT

Florida DOT states that the engineer may allow a maximum target slump flow spread of 27 inches for SCC with VMA and 24 inches for SCC without VMA. The Florida DOT specifies that the difference between the slump flow and the J-ring spread be less than 2 inches, the slump flow time, T_{500}, be 2 to 7 seconds, and the VSI not to exceed 2.

2.5.4 Michigan DOT

The Michigan DOT specifies the following SCC fresh properties requirements (Michigan 2005):

- Slump flow equal to 27 in ± 1.0 in
- VSI rating equal to or less than 1
- J-ring value between 0.5 in and 0.6 in (procedure from PCI)
- L-box ratio greater than 0.8 (80%)

3. SCC STANDARD TESTS

This chapter covers the standard tests used in this research to measure the aggregate properties, fresh concrete properties, and hardened concrete properties of the SCC. The results of these tests are presented in Section 4.

3.1 Aggregate Testing

The aggregates used for the SCC in this research were received at the laboratory in large bins. The aggregate samples were reduced for testing according to ASTM C 702-98: "Standard Practice for Reducing Samples of Aggregate to Testing Size" (ASTM 2006). Samples were dried to an oven-dry state and reduced in size utilizing a mechanical splitter, Method A in ASTM C 702. The sample was placed in a pan and distributed evenly from edge to edge of the mechanical splitter. This process was repeated until samples were the size required for each test.

The tests performed to evaluate the properties of the aggregates used were ASTM C29: "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate," ASTM C136: "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates," ASTM C127: "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate," ASTM C128: "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate," and ASTM C117: "Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve by Washing" (ASTM 2006). The procedures used in this research are presented in the following section. The results of the aggregate tests are presented in this Section 4.

3.1.1 Bulk Density

The bulk densities of the aggregates were measured according to ASTM C 29-97: "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate" (ASTM 2006). The measure used was calibrated by filling it with room temperature water and using Table 3 of ASTM C 29 to determine the density of the water. The difference between the weight of the measure filled with water and the weight of the empty measure was used to determine the weight of the water the measure contained. The density and weight of the water were used to calculate the volume of the measure. Temperatures were measured in degrees Fahrenheit; weights were measured in kilogram-force. The volume of the measure was determined in cubic meters.

The aggregate sample was oven dried to a constant mass and cooled to a comfortable handling temperature. The measure was filled in three even layers. When each layer was placed in the measure, it was rodded with a tamping rod for 25 strokes to determine the compact bulk density. The last layer filled the measure to overflowing and after rodding was leveled using a straightedge. The difference between the weight of the measure filled with aggregate and the weight of the empty measure was used to determine the weight of aggregate the measure contained. The weight of the aggregate was divided by the volume of the measure to calculate the compact bulk density of the aggregate. The bulk densities were determined in kg/m^3 and converted to lb/ft^3.

3.1.2 Particles Finer than No. 200

The amount of aggregate material finer than a 75-µm (No. 200) sieve was determined according to ASTM C 117-04: "Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing" (ASTM 2006). The aggregate sample was oven dried to a constant mass. Procedure A was followed, washing the aggregate with only plain water. The aggregate was covered with water and agitated to separate the particles finer than 75 µm from the coarser particles and bring the finer particles into suspension. The water with the suspended particles was poured over a 75-µm sieve. The process of covering the aggregate with water, agitating, and pouring off the water with the suspended finer particles was repeated until the water was clear. The retained material was oven dried to constant mass. Mass was determined in units of kilograms. The amount of material passing through the 75-µm sieve was determined as a percentage of the mass of the original sample. The amount of material passing through the 75-µm sieve by washing was used in calculating the particle size distribution of the fine aggregates.

3.1.3 Sieve Analysis

The particle size distributions of the aggregates were measured according to ASTM C 136-05: “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates” (ASTM 2006). The aggregates were first washed according to ASTM C 117 to determine the amount of material finer than the 75-µm (No. 200) sieve. The aggregates were then oven dried to a constant mass and cooled to a comfortable handling temperature. The mass of the total sample was measured. The aggregate sample was sieved over nested sieves by shaking on a mechanical shaker for approximately 10 minutes. The sieves used for the fine and coarse aggregate samples are listed in Table 3.1 and 3.2, respectively.

Table 3.1 Sieves Sizes for Fine Aggregate Gradation

Sieve Size (µm)	Sieve No.
9500	3/8"
4750	No. 4
2360	No. 8
1180	No. 16
600	No. 30
300	No. 50
150	No. 100
75	No. 200
0	Pan

Table 3.2 Sieve Sizes for Coarse Aggregate Gradation

Sieve Size (µm)	Sieve No.
25.4	1"
19.05	3/4"
12.7	1/2"
9.525	3/8"
4.75	No. 4
0	Pan

The mass retained on each sieve was measured. The amount of material passing the 75-µm (No. 200) sieve as determined by ASTM C 117 was added to the amount determined from sieve analysis. The measured retained masses were used to calculate the percentage of the total mass passing each sieve.The fineness modulus was also calculated for the fine aggregates. The fineness modulus was calculated by dividing by 100 the cumulative percentage retained on the 150-µm (No. 100), 300-µm (No. 50), 600-µm (No. 30), 1.18-mm (No. 16), 2.36-mm (No. 8), 4.75-mm (No. 4), and 9.5-mm (3/8-in) sieves.

3.1.4 Density, Specific Gravity, and Absorption

The densities, relative densities (specific gravities), and absorptions of the aggregates were measured according to ASTM C 127-04: "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate" and ASTM C 128-04a: "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate" (ASTM 2006).

The coarse aggregate sample was oven dried to a constant mass and cooled to a comfortable handling temperature. The aggregate sample was then covered with room temperature water and left submerged in water for 24 hours. The aggregate was then removed from the water and placed on a large towel. The aggregate was rolled in the towel to a saturated surface-dry (SSD) condition. A SSD condition occurs when all visible film of water has been eliminated while water in pores has not evaporated. The mass of the SSD aggregate sample in air was measured. The apparent mass of the SSD aggregate sample in room temperature water was then measured. The aggregate sample was oven dried to a constant mass and then cooled to a comfortable handling temperature. The mass of the dry aggregate sample was measured.

The density, relative density (specific gravity), and absorption of the coarse aggregate were calculated using the measured masses according to ASTM C 127. In calculating the density of the aggregate, the density of water at room temperature was taken as 997.5 kg/m^3 (62.27 lb/ft^3). Equations 3.1, 3.2, 3.3, and 3.4, as found in ASTM C 127 (ASTM 2006), were used to perform the calculations.

$$\text{SSD relative density (specific gravity)} = \frac{\text{B}}{\text{B - C}} \tag{3.1}$$

$$\text{SSD density, kg/m}^3 = 997.5\left(\frac{\text{B}}{\text{B - C}}\right) \tag{3.2}$$

$$\text{SSD density, lb/ft}^3 = 62.27\left(\frac{\text{B}}{\text{B - C}}\right) \tag{3.3}$$

$$\text{Absorption, \%} = \left(\frac{\text{B - A}}{\text{A}}\right)100 \tag{3.4}$$

where:

A = mass of oven less dry test sample in air

B = mass of saturated surface-dry sample in air

C = apparent mass of saturated test sample in water

The fine aggregate was tested according to ASTM C 128 (ASTM 2006). The fine aggregate was oven dried to a constant mass and cooled to a comfortable handling temperature. The aggregate was then covered with room temperature water and left immersed in water for 24 hours. Excess water was removed carefully by not agitating the sample to avoid loss of fine material. The sample was then dried by exposing the aggregate to warm air and stirring frequently. When the sample approached SSD condition, while still having some water on the surface, the test for surface moisture was performed according to ASTM C 128.

The mold for the test for surface moisture was filled by placing the fine aggregate to overflowing, heaping additional aggregate above the mold, and tamping the aggregate with 25 drops of the tamper. The aggregate around the base of the mold was removed and the mold was then lifted. The aggregate was considered to have excess surface moisture if the aggregate maintained the shape of the mold. The SSD condition was considered to have occurred if the aggregate slumped after the mold was lifted.

As soon as the SSD condition was reached, the density, specific gravity, and absorption of the fine aggregate was determined according to the gravimetric (pycnometer) procedure detailed in ASTM C 128. The mass of the pycnometer filled with room temperature water to the calibration mark was determined before testing the aggregate. To test the fine aggregate, approximately 500 g of the SSD aggregate was placed into a pycnometer partially filled with water. After placing the aggregate in the pycnometer, it was filled to approximately 90% of the volume. The pycnometer was then manually rolled and agitated to remove the air bubbles in the sample. The pycnometer was then filled to the calibration mark with room temperature water and the total mass was determined. The aggregate was taken out of the pycnometer and placed in a pan to be oven dried to a constant mass and cooled to a comfortable handling temperature. The mass of the oven dried sample was then measured.

The measured mass of the oven dry sample, the saturated surface dry sample, the pycnometer filled with water to the calibration mark, and the pycnometer with the sample filled with water to the calibration mark were used to calculate the density, relative density (specific gravity), and absorption of the fine aggregate according to ASTM C 128. In calculating the density of the aggregate, the density of water at room temperature was taken as 997.5 kg/m^3 (62.27 lb/ft^3). Equations 3.5, 3.6, 3.7, and 3.8, as found in ASTM C 128 (ASTM 2006), were used to perform the calculations.

$$\text{SSD relative density} = \frac{S}{B + S - C} \tag{3.5}$$

$$\text{SSD density, kg/m}^3 = 997.5\left(\frac{S}{B + S - C}\right) \tag{3.6}$$

$$\text{SSD density, lb/ft}^3 = 62.27\left(\frac{S}{B + S - C}\right) \tag{3.7}$$

$$\text{Absorption, \%} = 100\left(\frac{S - A}{A}\right) \tag{3.8}$$

where:

A = mass of oven dry specimen

B = mass of pycnometer filled with water to calibration mark

C = mass of pycnometer filled with specimen and water to calibration mark

S = mass of SSD specimen

3.2 Fresh Concrete Testing

The SCC was sampled according to ASTM C 172-04: “Standard Practice for Sampling Freshly Mixed Concrete” (ASTM 2006), with some modifications. Samples were obtained in the time frame of 15 minutes from beginning to end in accordance with ASTM C 172. The sample was transported from the mixer by wheelbarrow a short distance into the laboratory. Prior to sampling, the SCC in the wheelbarrow was manually remixed by turning the concrete mix with a metal scoop. The slump spread, J-ring, temperature, and air content tests were performed within 5 minutes of sampling. According to ASTM C 172, two or more samples should be taken from the middle of a batch for testing. Due to the small size of each batch (one-tenth of a cubic yard), the entire batch was used for sampling.

The tests performed to evaluate the fresh concrete properties were ASTM C 231: “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method,” ASTM C 1611: “Standard Test Method for Slump Flow of Self-Consolidating Concrete,” ASTM C 1621: “Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring,” ASTM C 1064: “Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete” (ASTM 2006), the L-box test according to the Interim Guidelines for the Use of Self-Consolidating Concrete in Precast/Prestressed Concrete Institute Member Plants (PCI 2003), and the column segregation test. The column segregation test was not an ASTM standard at the time of testing, but it was later approved as ASTM C 1610: “Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique” (ASTM 2006). The procedures used in this research are presented in the following section. The results of the fresh concrete tests are presented in Section 4.

3.2.1 Temperature

The temperatures of the SCC mixes were measured according to ASTM C 1064-05: “Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete” (ASTM 2006). A thermometer was used to measure the temperature. The thermometer was placed after discharge in a form with at least 3 inches of cover. The temperature was recorded after the reading on the thermometer had stabilized. The temperature was recorded in degrees Fahrenheit and converted to degrees Celsius.

3.2.1 Air Content

The air contents of the SCC mixes were measured using a Type B pressure meter according to ASTM C 231-04: “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method” (ASTM 2006). The pressure meter is shown in Figure 3.1.

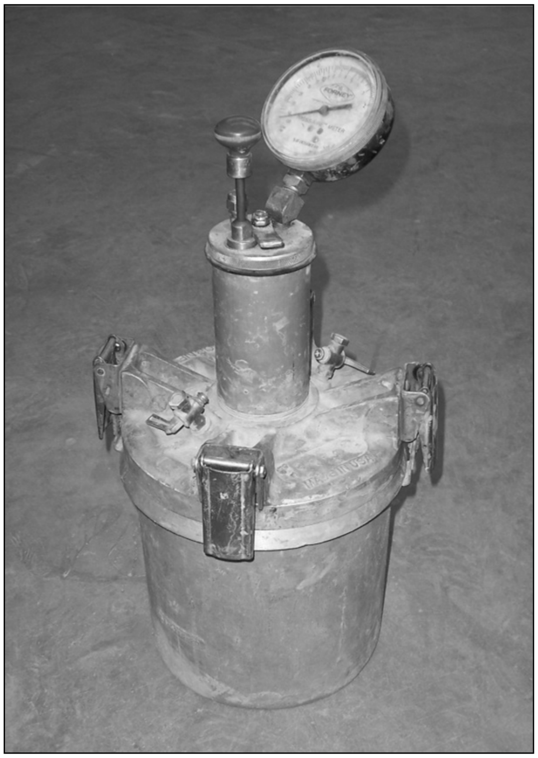


Figure 3.1 Pressure Meter for Measuring Air Content

The measuring bowl and cover were dampened first. The SCC was then placed in the container. As a modification to ASTM C 231, the SCC was placed in one layer without rodding instead of three equal layers with rodding. The surface was struck off in accordance with ASTM C 231, and the rim was wiped clean with a sponge. The cover was placed on the bowl and clamped. Water was injected into the testing apparatus through one of the open petcocks until water free from air bubbles flowed out from the other open petcock. Air was pumped into the apparatus until the pressure was stabilized at the calibrated gage value. Both petcocks were then closed. The air valve between the bowl and the air chamber was opened simultaneously with the bowl being struck with a rubber mallet. The air content was read from the gage and recorded.

3.2.3 Slump Spread and T_{500}

The flowability of the SCC was determined using ASTM C 1611-05: “Standard Test Method for Slump Flow of Self-Consolidating Concrete” (ASTM 2006). The test was performed on a non-absorbent plastic board or base plate. The board was marked with concentric circles. The innermost circle indicated the location where the slump cone should be placed. The outermost circle marked the 500 mm (20 inches) diameter to facilitate the performance of the T_{500} (T_{20}) test. The base plate also included a mark where the J-ring should be placed. The J-ring test is described in a later section. The base plate is shown in Figure 3.2.

Figure 3.2 Base Plate for Slump Flow and J-Ring Tests

The slump mold and base plate were moistened. The mold was filled according to Procedure B in ASTM C 1611 using an inverted mold. The mold was filled in one lift without any rodding. The surface was struck off and any excess concrete was removed from the base plate. The mold was then lifted vertically approximately 9 inches in a steady motion and within 2 to 4 seconds. When the concrete had stopped flowing on the board, the diameter of the spread of the SCC was measured in two perpendicular directions. The average of the two measurements was recorded. A higher slump flow indicates better filling ability, or the ability of the concrete to flow under its own weight. The slump flow test and the slump spread tests are shown in Figures 3.3 and 3.4, respectively.

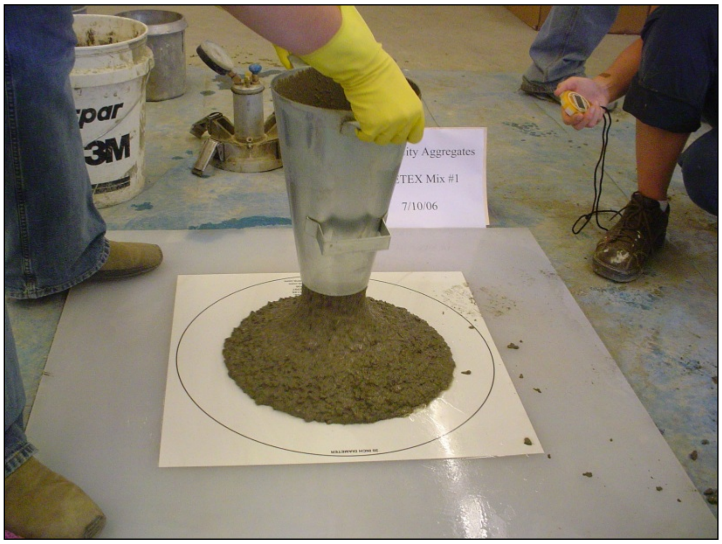


Figure 3.3 Slump Spread Test in Progress

Figure 3.4 Slump Spread

As the slump test was being performed, the T_{500} (or T_{20}) test was also performed. This test is a measure of viscosity of the SCC. Information about the T_{500} (T_{20}) test is given in the appendix of ASTM C 1611. A stopwatch was used to measure the time from the instant the mold was lifted until the concrete crossed the 500 mm (20 in) diameter circle.

3.2.4 Visual Stability Index

ASTM C1611-05: “Standard Test Method for Slump Flow of Self-Consolidating Concrete” (ASTM 2006) also includes a relative measure of stability called the visual stability index (VSI). The VSI is evaluated using the concrete spread from the slump flow test. Information about VSI is included in the appendix of ASTM C 1611. The VSI criteria as shown in ASTM 1611 are also shown in Table 3.3. ASTM C 1611 also includes figures used as examples for VSI values (ASTM 2006).

Table 3.3 Visual Stability Index Scale (ASTM 2006)

Sieve Size (µm)	Sieve No.
0 = Highly Stable	No evidence of segregation or bleeding.
1 = Stable	No evidence of segregation and slight bleeding observed as a sheen on the concrete mass.
2 = Unstable	A slight mortar halo ≤ 10 mm (0.5 in) and/or aggregate pile in the center of the concrete mass.
3 = Highly Unstable	Clearly segregating by evidence of a large mortar halo > 10 mm (0.5 in) and/or a large aggregate pile in the center of the concrete mass.

3.2.5 J-Ring Spread

The passing ability of the SCC was evaluated according to ASTM C 1621-06: “Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring” (ASTM 2006). The test was performed on a base plate described in Section 3.2.3. The J-ring apparatus was made out of steel and dimensioned according to ASTM C 1621. The ring was fitted with 16-16 mm (⅝″) diameter rods equally spaced around a 12″–diameter circle.

The slump mold and base plate were moistened. The mold was filled according to Procedure B in ASTM C 1621 using an inverted mold. The mold was filled in one lift without any rodding or vibrating. The surface was struck off and any excess concrete was removed from the base plate. The mold was then lifted vertically approximately 9 inches in a steady motion. When the concrete had stopped flowing, the diameter of the spread of the SCC through the J-ring was measured in two perpendicular directions and averaged.

The difference in the diameter of the slump flow test and the diameter of the flow through the J-ring was used to assess the amount of blocking that was occurring for each mix. The relationship of the difference in these diameters to the amount of blocking is given in ASTM C 1621 and presented in Table 3.4. The J-ring spread is shown in Figure 3.5.

Table 3.4 Blocking Assessment (ASTM 2006)

Difference Between Slump Flow and J-Ring Flow	Blocking Assessment
0 to 25 mm (0 to 1″)	No visible blocking.
>25 to 50 mm (>1″ to 2″)	Minimal to noticeable blocking
>50 mm (> 2″)	Noticeable to extreme blocking

Figure 3.5 J-Ring Spread

3.2.6 L-Box

The L-box test was performed in an apparatus shaped like an “L”. The L-box consists of two segments, one horizontal and one vertical, separated by an opening that has a grid of vertical bars and covered with a sliding gate. Details of the apparatus are shown in Figure 3.6.

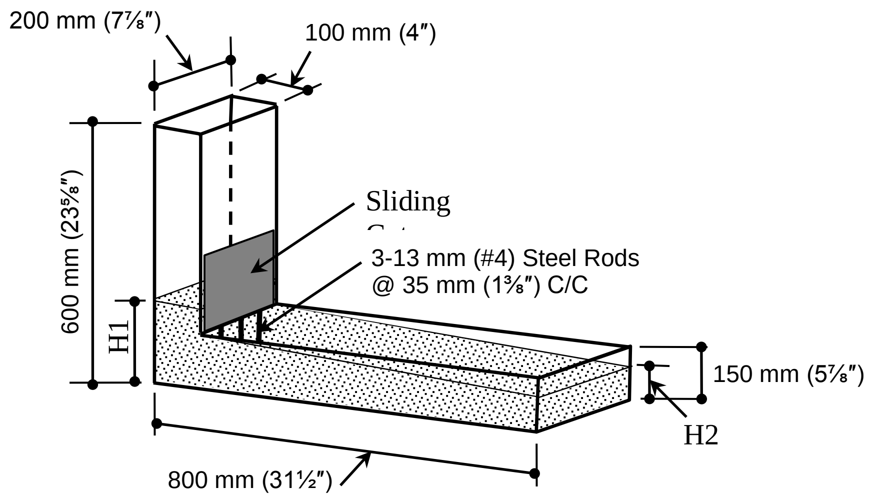


Figure 3.6 Details of the L-Box Test Apparatus

The L-box was dampened. The sliding gate was closed and the vertical section of the L-box was filled with concrete. The concrete was not rodded or vibrated. The sliding gate was lifted to allow the concrete to flow into the horizontal section of the L-box. The heights of the concrete in the vertical section (H1) and the horizontal section (H2) were measured and the blocking ratio H2/H1 was calculated. The ratio of H2 to H1 was used to determine the blocking ratio. A blocking ratio closer to one indicates a more flowable concrete and better passing ability through reinforcement. Most literature suggests a minimum blocking ratio of 0.8 (EFNARC 2002). The L-box test is shown in Figure 3.7 (measuring H2).

Figure 3.7 L-Box Test

3.2.7 Column Segregation

The column segregation test was performed in this study to measure static segregation of the SCC mix. At the time of testing, the column segregation test had not been standardized yet. It was later approved as ASTM C 1610-06: “Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique” (ASTM 2006). The procedure used in research was the same as the procedure in ASTM 1610 with a slight modification.

The column segregation test was performed in a column made of three cylindrical sections of PVC. The column mold had an inner diameter of 200 mm (8 in). The top section and bottom section heights were 165 mm (6.5 in), and the middle section height was 330 mm (13 in). The bottom section was attached to a 300 mm (12 in) square base for stability. The column segregation test apparatus is shown in Figure 3.8.

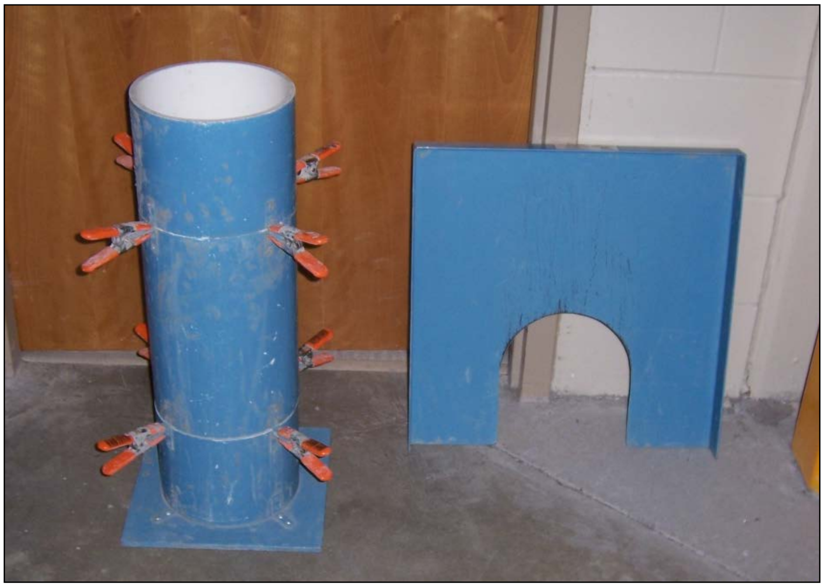


Figure 3.8 Column Segregation Test Apparatus

The column mold was filled with SCC by using a plastic pail. The SCC was not rodded or vibrated. The excess SCC was removed by using a strike-off bar in accordance with ASTM C 1610. The SCC remained in the mold without disturbance for 15 minutes. The top section of the column including the concrete within was removed by separating it from the middle section using a steel collector plate. The concrete from the top section was placed into a plastic pail. The middle section was then separated from the bottom section following the same approach used to separate the top section. The concrete from the middle section was discarded while the concrete from the bottom section was placed into a plastic pail. The concrete from the top and bottom sections was washed separately over a 4.75 mm (No.4) sieve so that only coarse aggregate remained on the sieve. In this research, the coarse aggregate was oven dried to a constant mass. According to ASTM C 1610 which came out after the experimental work of this study was completed, the coarse aggregate should be dried to a saturated surface dry condition. The mass of the coarse aggregate in the top (CA_T) was compared to the mass of the coarse aggregate in the bottom (CA_B) to evaluate the amount of static segregation (S) occurring in the SCC. The static segregation was determined according to ASTM C 1610 (ASTM 2006), as shown in Equations 3.9 and 3.10. A smaller difference indicates better resistance to segregation. The column segregation test is more suited for a laboratory test than for a field test for acceptance.

$$S = 2\left[\frac{CA_B - CA_T}{CA_B + CA_T}\right]100, \quad \text{if } CA_B > CA_T \tag{3.9}$$

$$S = 0, \quad \text{if} \ \ CA_B \le CA_T \tag{3.10}$$

3.3 Hardened Concrete Testing

For this study, the hardened concrete tests performed on SCC were the same as those that would be performed for conventional concrete. The hardened SCC cylinders and beams were made according to ASTM C 192-06: “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory” (ASTM 2006), with some modifications. The SCC was not rodded when placing it in the cylinders and beams, unlike what is specified in the standard for conventional concrete. The specimens were leveled off using a strike-off bar and covered. After approximately 24 hours, the specimens were removed from the molds and moist cured until tested.

The tests performed to evaluate the hardened properties of the SCC were ASTM C 39: “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,” ASTM C 78: “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading),” ASTM C 496: “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens” (ASTM 2006), and AASHTO draft “Standard Method of Test for Static Segregation of Hardened Self-Consolidating Concrete Cylinders” (AASHTO 2005). The results of the hardened concrete tests are presented in Section 4.

3.3.1 Compressive Strength

The compressive strength (f'_c)of the SCC specimens was tested according to ASTM C 39-05: “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens” (ASTM 2006). The compressive strength of the SCC was tested for each batch after moist curing for 7 days and 28 days. The plastic cylinder molds used for casting the concrete cylinders had an inner diameter of 152 mm (6 inches) with a height of 305 mm (12 in). Steel bearing caps with neoprene pads were used to cap the concrete cylinders. A Baldwin concrete testing machine with a maximum load capacity of 300,000 lbs was used to test the cylinders in compression. A compressive load was applied continuously to the cylinder. After failure, the maximum compressive load was recorded and used to calculate the compressive strength of the specimen.

3.3.2 Splitting Tensile Strength

The splitting tensile strength (f_{ct}) of the hardened SCC was measured according to ASTM C 496-04: “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens” (ASTM 2006). A plywood strip was placed on the lower bearing block and the cylinder was centered lengthwise on the plywood strip. Another plywood strip was centered on the top of the cylinder diametrically opposite to the bottom strip. A compressive load was applied continuously to the edges of cylinder. The cylinder failed along a plane extending between the two loaded edges. After failure, the maximum compressive load was recorded and used to calculate the splitting tensile strength of the specimen according to Equation 3.11 (ASTM 2006).

$$f_{ct} = \frac{2\,\mathrm{P_u}}{\pi\,\mathrm{L}\,\mathrm{D}} \tag{3.11}$$

where

$\mathrm{P_u}$ = Maximum applied load

L = Length of specimen

D = Diameter of specimen

3.3.3 Modulus of Rupture

The modulus of rupture (f_r) of the SCC was measured according to ASTM C 78-02: “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)” (ASTM 2006). The beam specimens used were 152 mm wide x 152 mm deep x 559 mm long (6″ x 6″ x 22″). Each specimen was supported at 51 mm (2 in) from each end and loaded at the one-third points between the supports until failure. The modulus of rupture was calculated according to Equation 3.12 (ASTM 2006).

$$f_r = \frac{P_u L}{W D} \tag{3.12}$$

where

P_u = Maximum applied load

L = Length of specimen

D = Average depth of specimen

W = Average width of the specimen

3.3.4 Hardened Visual Stability Index

The static segregation of the SCC was measured using AASHTO’s draft “Standard Test Method of Test for Static Segregation of Hardened Self-Consolidating Concrete Cylinders” (AASHTO 2005). The concrete cylinders used were 152 mm (6 inches) in diameter and 305 mm (12 in) high. The hardened cylinders were sawn in half lengthwise. The static segregation was visually assessed according to the criteria in the AASHTO test method using a hardened visual stability index (HVSI) scale. Information about HVSI is included in the AASHTO document. The HVSI criteria as shown in the test method to evaluate HVSI are presented in Table 3.5. The AASHTO document also includes figures used as examples for assigning HVSI values (AASHTO 2005).

Table 3.5 Hardened Visual Stability Index Rating Criteria (AASHTO)

Rating	Criteria
0 = Highly Stable	No mortar layer at the top of the cut plane and no variance in size and percent area of coarse aggregate distribution from top to bottom.
1 = Stable	No mortar layer at the top of the cut plane but slight variance in size and percent area of coarse aggregate distribution from top to bottom.
2 = Unstable	Slight mortar layer, less than 25 mm (1 in) tall, at the top of the cut plane and distinct variance in size and percent area of coarse aggregate distribution from top to bottom.
3 = Unstable	Clearly segregated as evidenced by a mortar layer greater than 25 mm (1 in) tall and/or considerable variance in size and percent area of coarse aggregate distribution from top to bottom.

4. EXPERIMENTAL WORK AND RESULTS

4.1 Introduction

This section covers the results of the laboratory tests performed to evaluate the properties of the aggregates used in the SCC mixes and the properties of the fresh and hardened SCC. Procedures for the standard tests that were performed in this study can be found in the ASTM Annual Book of Standards (2006). Some conclusions based on the results are also presented in this section.

Twelve SCC mixes were studied. The parameters were aggregate type, w/c ratio, and mixing duration. The mixes were developed for two types of coarse aggregates: two-stage crushed quartzite (eastern South Dakota) and crushed limestone (western South Dakota). Three w/c ratios, 0.38, 0.42, and 0.46, were investigated. Two mixing durations were utilized to simulate precast and cast-in-place applications.

4.2 Aggregate Testing and Results

The aggregates used for preparing the SCC mixes in this study were tested to establish their properties before mixing began. The tests performed to evaluate the properties of the aggregates were ASTM C29: “Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate,” ASTM C136: “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates,” ASTM C127: “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate,” ASTM C128: “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate,” and ASTM C117: “Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve by Washing” (ASTM 2006). The procedures followed for these tests are located in Section 3.1. The data from the aggregate tests is located in Appendix B. The samples were reduced according to ASTM C 702: “Standard Practice for Reducing Samples of Aggregate to Testing Size” (ASTM 2006).

Two coarse and three fine aggregates from eastern and western South Dakota were selected and used for the SCC mixes in this study. The aggregates were identified by the pit name and pit location as “Pit Name/Pit Location.” The western South Dakota fine aggregate tested was Birsdall/Creston Sand, which will be referred to as the Rapid City Sand. The western coarse aggregate tested was Pete Lien Quarry/Rapid City 3/8” Limestone, which will be referred to as Rapid City Limestone. The Rapid City aggregates were used for both the precast and cast-in-place mixes. Two eastern South Dakota fine aggregates were used, Bitterman/Mitchell Sand, which will be identified as Mitchell Sand 1, and Opperman/Fort Randall Sand, which will be identified as Mitchell Sand 2. Mitchell Sand 1 was used for the eastern South Dakota precast mixes, and Mitchell Sand 2 was used for eastern South Dakota cast-in-place mixes. The eastern South Dakota coarse aggregate used was Sioux Falls Quarry/Sioux Falls Two-Stage Crushed Quartzite, referred to as Sioux Falls Quartzite. The selection of the aggregate sources was performed by SDDOT.

Initially, three types of coarse aggregates were considered for potential use in this study. The three types of coarse aggregates (Rapid City Limestone, 2-stage Crushed Quartzite, and Flat and Elongated Quartzite) are shown in Figure 4.1. The figure shows the difference in shape and size of the aggregates.

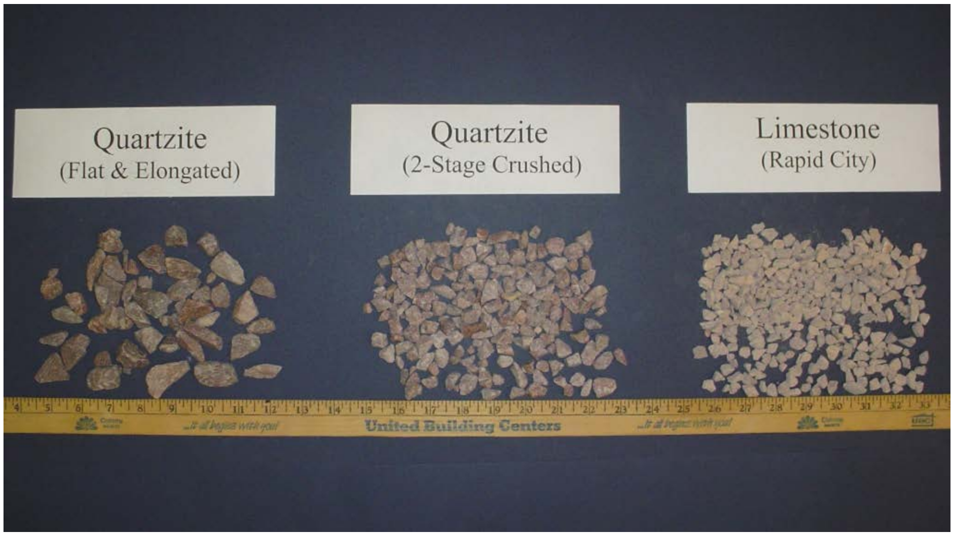


Figure 4.1 Types of Coarse Aggregates Considered in the Study

The Rapid City Limestone and Sioux Falls 2-Stage Crushed Quartzite, shown together in Figure 4.2, were used for preparing the SCC mixes in this study. The two aggregates are fairly similar in shape and size. The third coarse aggregate is Spencer Quarry/Spencer 1/2″ Quartzite. By visual inspection, the Spencer aggregate showed a high content of flat and elongated shape particles. Flat and elongated is defined by ASTM D 4791: "Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate" (ASTM 2006) as aggregate with a length to thickness ratio "greater than a specified value." In this study, a particle with an aspect ratio of 5 or more was considered to be flat and elongated. The two types of quartzite aggregates are shown together in Figure 4.3. Large coarse particles and flat and elongated aggregates are not suitable for use as aggregate in SCC because there is more interlock between the particles than between aggregate particles with a rounder shape. This interlock hinders flowability and may lead to blockage (Pellerin 2005; Collepardi 2005). Because the Spencer quartzite is larger and more flat and elongated than the Sioux Falls quartzite, the Spencer quartzite was judged to be unsuitable for producing SCC for this project.

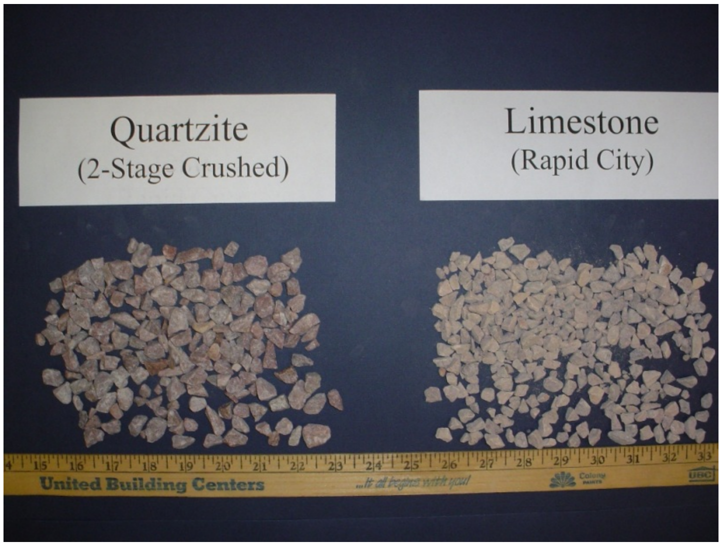


Figure 4.2 Types of Coarse Aggregates Used in the Study

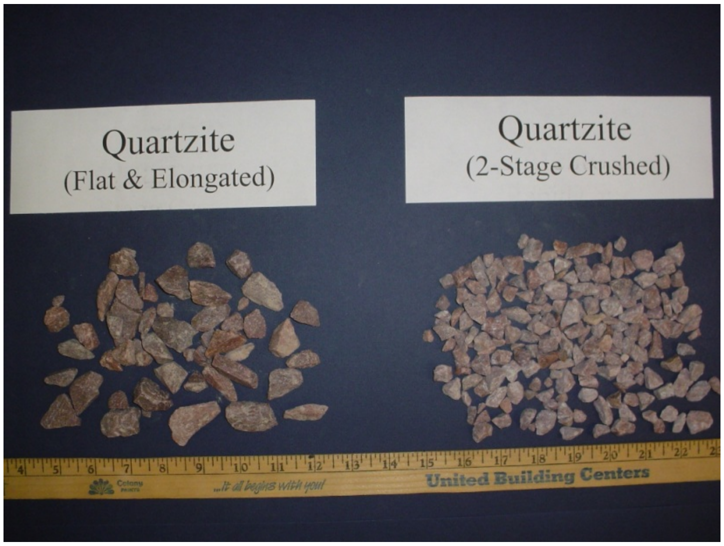


Figure 4.3 Quartzite Aggregates Considered for the Study

4.2.1 Bulk Density

The bulk densities of the aggregates were measured following ASTM C29: “Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate” (ASTM 2006). The measured bulk densities for the aggregates in the oven dry state are shown in Table 4.1. The values are reasonable and follow what is expected for coarse aggregates and sands.

Table 4.1 Bulk Densities of Aggregates

Aggregate	Dry Bulk Density kN/m^3 (lb/ft^3)
Rapid City Limestone	15.33 (97.6)
Rapid City Sand	16.04 (102.1)
Sioux Falls Quartzite	16.43 (104.6)
Mitchell Sand 1	17.34 (110.4)
Mitchell Sand 2	17.58 (111.9)

4.2.2 Density, Specific Gravity, and Absorption

Multiple samples of each aggregate were tested for saturated surface dry (SSD) density, SSD specific gravity, and absorption following ASTM C127: “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate,” and ASTM C128: “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate” (ASTM 2006). The results for each aggregate type were averaged and tabulated. Three samples of each of the coarse aggregates were tested. Six samples were tested for each of the Rapid City Sand and the Mitchell Sand 1, and four samples were tested for the Mitchell Sand 2. The average measured SSD densities, SSD specific gravities, and absorptions for the aggregates are shown in Table 4.2. The values are reasonable and follow what is expected of these aggregates.

Table 4.2 Bulk Densities of Aggregates

Aggregate	SSD Density kN/m^3 (lb/ft^3)	SSD Specific Gravity	Absorption %
Rapid City Limestone	25.91 (164.9)	2.65	0.36
Rapid City Sand	25.78 (164.1)	2.64	1.09
Sioux Falls Quartzite	25.76 (164.0)	2.63	0.34
Mitchell Sand 1	25.48 (162.2)	2.61	0.30
Mitchell Sand 2	25.51 (162.4)	2.61	0.32

4.2.3 Gradation and Fineness Modulus

The gradations and fineness modulus values were measured following ASTM C136: “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates” and ASTM C117: “Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve by Washing” (ASTM 2006).

SCC requires a coarse aggregate size that is usually smaller than that used in conventional concrete. The special provision for Self-Consolidating Concrete for Box Culverts, which was developed as part of this research, specifies minimum and maximum percent passing values on the coarse aggregates to be used with SCC mixes. Figures 4.4 and 4.5 show the measured gradation for the coarse aggregates along with the minimum and maximum percent passing values specified in the special provisions. The special provision for Self-Consolidating Concrete for Box Culverts can be found in Appendix C. The measured gradation was within the limits specified in the Special Provisions.

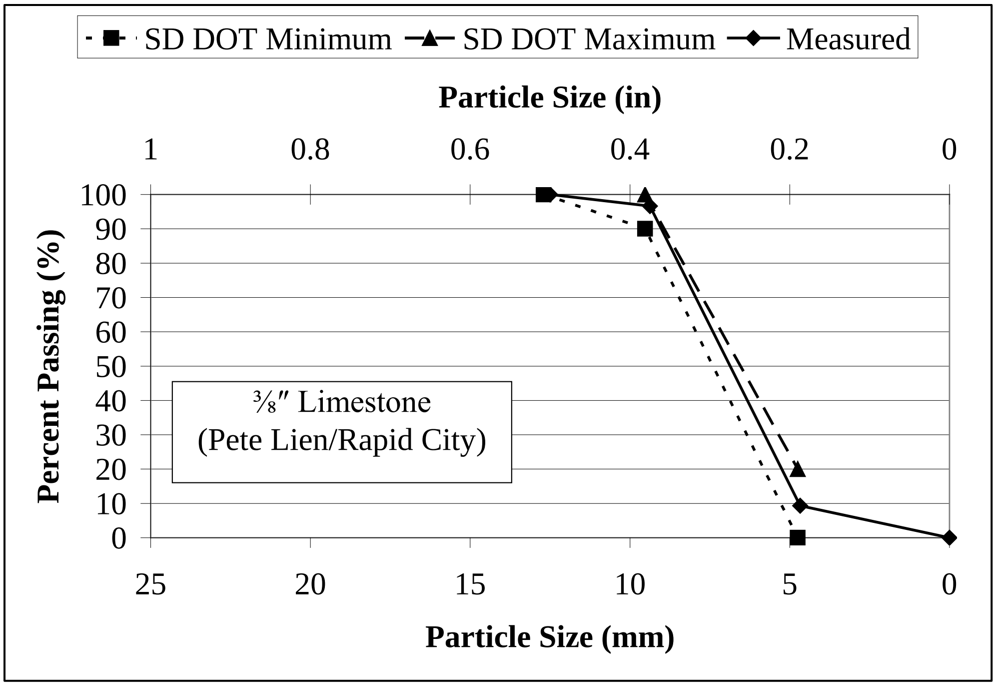


Figure 4.4 Gradation of Rapid City Limestone

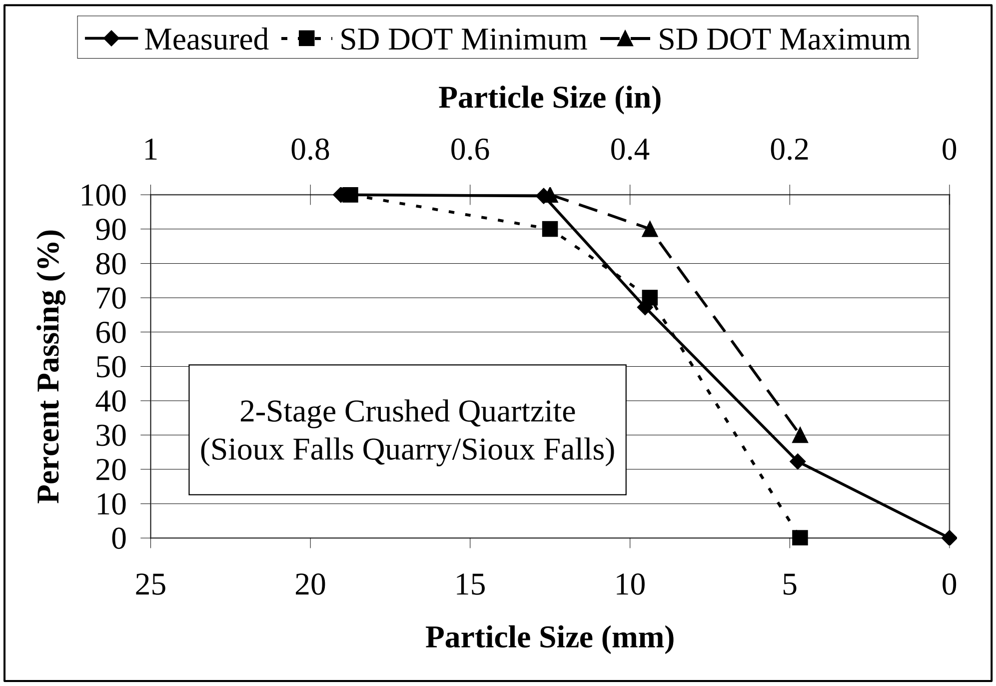


Figure 4.5 Gradation of Sioux Falls Quartzite

The gradations of the fine aggregates are shown in Figures 4.6, 4.7 and 4.8. These figures also show the minimum and maximum percent passing values for the aggregates as specified in the SD-DOT Standard Specification for Roads and Bridges (SD 2004). It should be noted that the measured gradations of all of the fine aggregates were within the limits of the SDDOT Standard Specification.

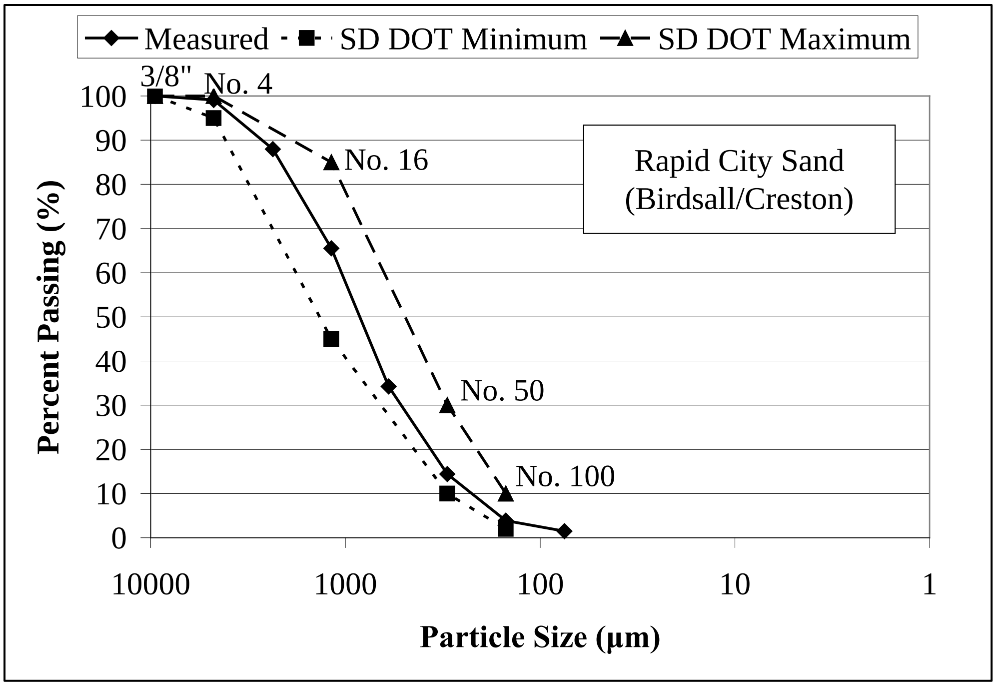


Figure 4.6 Gradation of Rapid City Sand

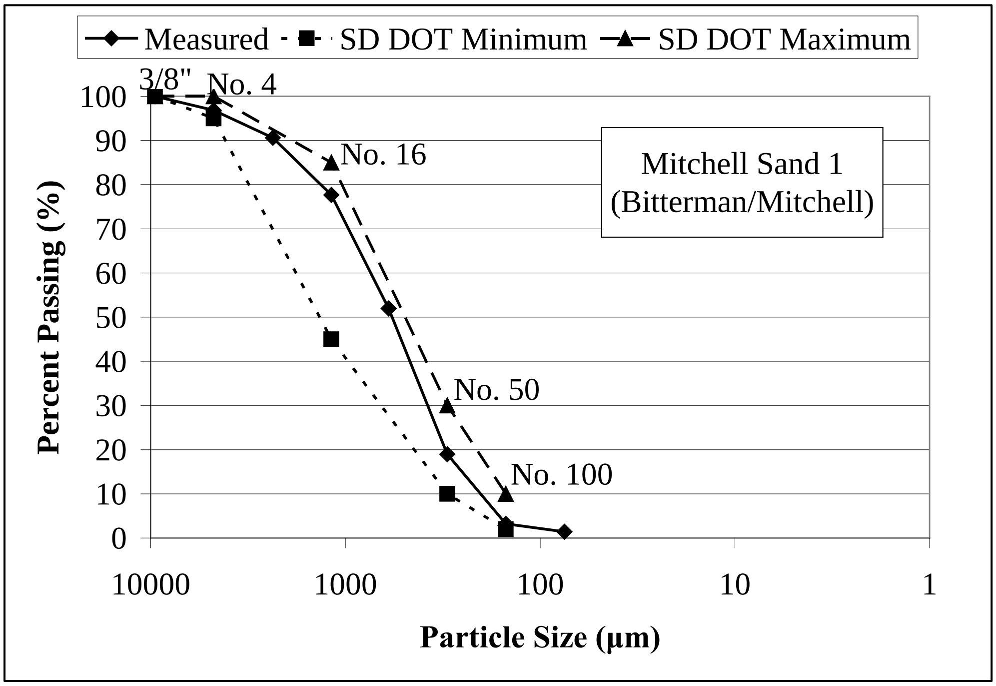


Figure 4.7 Gradation of Mitchell Sand 1

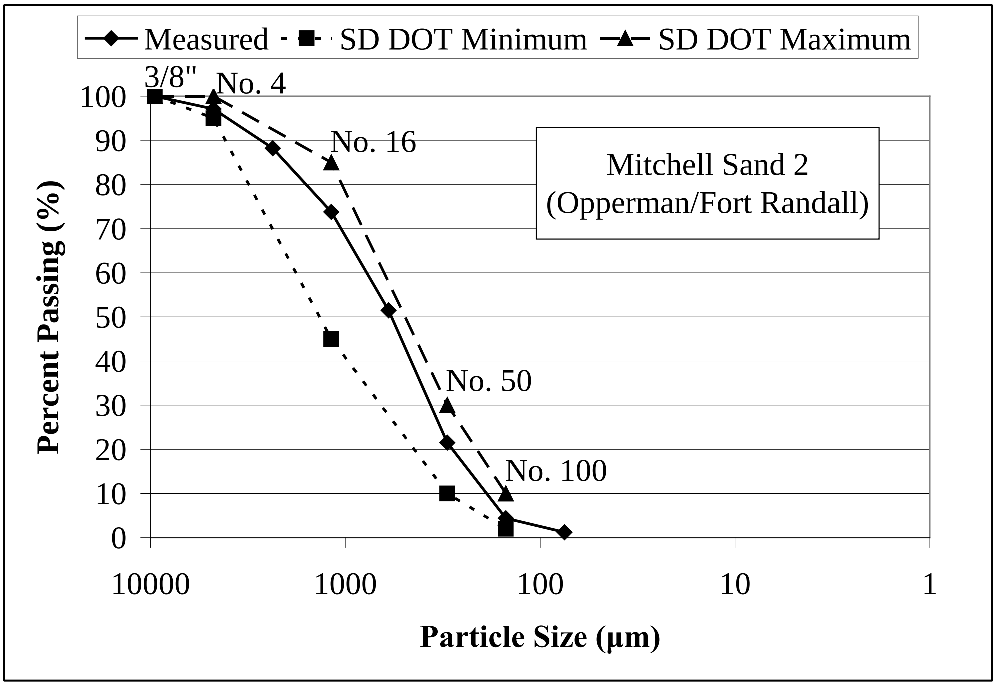


Figure 4.8 Gradation of Mitchell Sand 2

The fineness modulus values found from the gradations of the fine aggregates are shown in Table 4.3. The gradations and fineness modulus values for Mitchell Sand 1 were very similar to those for Mitchell Sand 2, leading to the conclusion that the two aggregates may have similar effects on the SCC mix properties.

Table 4.3 Fineness Modulus of Aggregates

Aggregate	Fineness Modulus
Rapid City Sand	2.95
Mitchell Sand 1	2.61
Mitchell Sand 2	2.64

4.3 Mix Design and Preparation

Twelve mixes were tested and investigated in this study. Of the twelve mixes, six were developed using regional aggregates from eastern South Dakota. The other six mixes were developed using regional aggregates from western South Dakota. For each region, three of the six mixes were intended for precast applications and the other three mixes were intended for cast-in-place applications. The mixes developed with the western South Dakota aggregates were classified as Rapid City precast (R-PC) and Rapid City cast-in-place (R-CIP). The mixes developed with the eastern South Dakota aggregates were classified as Mitchell precast (M-PC) and Mitchell cast-in-place (M-CIP). For each mix classification, three w/c ratios, 0.38, 0.42, and 0.46, were used. Table 4.4 presents a matrix of the mixes tested in this study.

The aggregate properties used for mixing concrete are described in the previous section. The cement used was GCC Dacotah Type I. Three admixtures were used to prepare the SCC mixes. The air entrainer used was Daravair® M. The set retarder used was Daratard® 17. The high range water reducing (HRWR) admixture, or superplasticizer, used was ADVA® Cast 555. The admixtures were developed and provided by W.R. Grace and Co. Literature on the admixtures used in this study can be found in Appendix D of this report.

Table 4.4 Matrix of Tested Mix Designs

	Western SD Local Aggregates		**Eastern SD Local Aggregates**	
Application	Precast	Cast-In-Place	Precast	Cast-In-Place
Classification	R-PC	R-CIP	M-PC	M-CIP
Coarse Aggregate	Rapid City Limestone	Rapid City Limestone	Sioux Falls Quartzite	Sioux Falls Quartzite
Fine Aggregate	Rapid City Sand	Rapid City Sand	Mitchell Sand 1	Mitchell Sand 2
W/C Ratios	0.38, 0.42, 0.48	0.38, 0.42, 0.48	0.38, 0.42, 0.48	0.38, 0.42, 0.48

The mix designs were initially based on a w/c ratio of 0.42. The base mix designs are shown in Table 4.5. The amounts of constituent materials used in the R-PC mixes were identical to those used in the respective R-CIP mixes. Although the M-PC and M-CIP mixes were made with different sand types, they contained identical amounts of constituent materials except for the air entrainer and the HRWR. The main difference between the CIP and the PC mixes was the duration of the mixing time. The CIP mixes were mixed thirty minutes longer than the PC mixes to simulate transport time between the batch plant and the construction site.

Table 4.5 Proposed Base Mix Designs

	Rapid City PC	**Rapid City CIP**	**Mitchell PC**	**Mitchell CIP**
Coarse, lb/cu yd	1293	1293	1293	1293
Fine, lb/cu yd	1495	1495	1495	1495
Cement, lb/cu yd	738	738	738	738
W/C ratio	0.42	0.42	0.42	0.42
Water lb/cu yd	310	310	310	310
Daravair M, oz/cwt	1.10	1.10	0.94	0.99
Daratard 17, oz/cwt	3.00	3.00	3.00	3.00
ADVA 555, oz/cwt	17.00	17.00	12.39	13.77

To create different mix designs, the w/c ratio was varied as the paste volume was kept constant. In determining the w/c ratio, the water in the admixtures was not included. The three w/c ratios used were 0.38, 0.42, and 0.46. The mix designs with varying w/c ratios are shown in Table 4.6 for the R-PC and R-CIP mixes, and in Tables 4.7 and 4.8 for the M-PC and M-CIP, respectively.

The concrete was mixed using a Whiteman WC-62 drum mixer. The drum was fitted with three fixed paddles as shown in Figure 4.9. Each SCC batch was one-tenth of a cubic yard. The batch size was limited because the flowable concrete would flow out of the mixer during mixing when the batch was too large. Two batches of each of the twelve mixes were required to perform all of the SCC tests.

Table 4.6 R-PC and R-CIP Proposed Mix Designs

W/C ratio	**0.38**	**0.42**	**0.46**
Coarse, lb/cu yd	1293	1293	1293
Fine, lb/cu yd	1495	1495	1495
Cement, lb/cu yd	780	738	700
Water lb/cu yd	297	310	322
Daravair M, oz/cwt	1.10	1.10	1.10
Daratard 17, oz/cwt	3.00	3.00	3.00
ADVA 555, oz/cwt	17.00	17.00	17.00

Table 4.7 M-PC Proposed Mix Design

W/C ratio	**0.38**	**0.42**	**0.46**
Coarse, lb/cu yd	1293	1293	1293
Fine, lb/cu yd	1495	1495	1495
Cement, lb/cu yd	780	738	700
Water lb/cu yd	297	310	322
Daravair M, oz/cwt	0.99	0.99	0.99
Daratard 17, oz/cwt	3.00	3.00	3.00
ADVA 555, oz/cwt	13.77	13.77	13.77

Table 4.8 M-CIP Proposed Mix Design

W/C ratio	**0.38**	**0.42**	**0.46**
Coarse, lb/cu yd	1293	1293	1293
Fine, lb/cu yd	1495	1495	1495
Cement, lb/cu yd	780	738	700
Water lb/cu yd	297	310	322
Daravair M, oz/cwt	0.94	0.94	0.94
Daratard 17, oz/cwt	3.00	3.00	3.00
ADVA 555, oz/cwt	12.39	12.39	12.39

For the experimental program of this study, the same mixing order was followed for all batches. The mixer drum was moistened to avoid adsorption of water from the mix to the walls of the drum. The aggregates were added to the mixer and combined, followed by adding and combining the cement. Initial water (80% of the total water) and air entrainer were added and combined into the mix. The set retarder was then added, followed by the final 20% water. The high range water reducing admixture (HRWRA) was added right after the final water for the precast mixes, and a half hour after the final water for the cast-in-place mixes. The additional half-hour mixing simulates the time a concrete mix would spend in a truck mixer before it arrives at a job site. In the case of cast-in-place mixes, the HRWRA would be added once the concrete arrives at the construction site and just before placing. After the HRWRA was added, the SCC was mixed until the HRWRA was dispersed and viscosity was developed in the mix. The mixing process following the addition of the HRWRA took approximately eight minutes.

Figure 4.9 The Concrete Mixer Used for Preparing the SCC Laboratory Batches

After mixing, the concrete was dispensed into a wheelbarrow and fresh concrete testing was performed, and hardened concrete testing specimens were prepared. The results of fresh and hardened concrete tests performed on the SCC mixes are found in sections 4.4 and 4.5.

4.4 Fresh Concrete Testing and Results

The concrete was sampled according to ASTM C 172: “Standard Practice for Sampling Freshly Mixed Concrete” (ASTM 2006). The tests performed to evaluate the fresh concrete were ASTM C 231: “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method,” ASTM C 1611: “Standard Test Method for Slump Flow of Self-Consolidating Concrete,” ASTM C 1621: “Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring,” ASTM C 1064: “Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete” (ASTM 2006), the L-box test according to the “Interim Guidelines for the Use of Self-Consolidating Concrete in Precast/Prestressed Concrete Institute Member Plants” (PCI 2003), and the column segregation test. The column segregation test was not an ASTM standard at the time of testing, but it was later approved as ASTM C 1610: “Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique” (ASTM 2006). The results of the fresh concrete tests are presented in this section. A summary of the results of these tests is presented in Table 4.9.

The SCC was not rodded for any of the fresh concrete tests. The cylinders and beams used for hardened concrete testing were made according to ASTM C31: “Standard Practice for Making and Curing Concrete Test Specimens in the Field” (ASTM 2006) without rodding. The hardened concrete cylinders and beams were cured in a laboratory moist cure room until tested. The results of the hardened concrete tests are presented in Section 4.5.

Table 4.9 Summary of Fresh Concrete Test Results

Mix Description	**Rapid City Cast-In-Place**						**Rapid City Precast**					
W/C	**0.46**		**0.42**		**0.38**		**0.46**		**0.42**		**0.38**	
Batch	2	1	2	1	2	1	2	1	2	1	2	1
Temperature, °C (°F)	26.7 (80.0)	26.1 (79)	26.9 (80.5)	29.2 (84.5)	26.1 (79.0)	26.9 (80.5)	26.1 (79.0)	24.2 (75.5)	24.7 (76.5)	27.5 (81.5)	23.3 (74.0)	27.8 (82.0)
Unit weight, kN/m^3 (lb/ ft^3)	22.16 (141.0)	21.61 (137.6)	21.60 (137.5)	21.87 (139.2)	22.29 (141.9)	22.29 (141.9)	22.16 (141.0)	22.08 (140.6)	22.24 (142.8)	22.40 (142.6)	22.17 (141.1)	22.60 (143.9)
Air content, %	7.9	8.6	9.0	8.1	7.9	8.1	6.0	7.2	7.2	7.0	8.0	7.0
Slump spread, mm (in)	578 (22.8)	521 (20.5)	549 (21.6)	511 (20.1)	492 (19.4)	489 (19.3)	556 (21.9)	572 (22.5)	591 (23.3)	530 (20.9)	556 (21.9)	553 (21.0)
Average slump spread, mm (in)	594 (21.6)		530 (20.9)		491 (19.3)		564 (22.2)		560 (22.1)		545 (21.4)	
T_{500} (T_{20}) slump, sec	0.99	1.76	1.07	1.51	†	†	1.89	0.90	1.09	1.70	1.87	3.07
VSI	0	0	0	0	0	0	0	0.5	0.5	0	0	0
J-ring spread, mm (in)	486 (21.8)	552 (19.1)	514 (20.3)	479 (18.9)	425 (16.8)	435 (17.1)	‡	558 (22.0)	568 (22.4)	‡	533 (21.0)	479 (18.9)
Average J-ring spread, mm (in)	519 (20.4)		497 (19.6)		430 (16.9)		558 (22.0)		568 (22.4)		506 (19.9)	
J-ring/slump spread difference, mm (in)	25 (1.0)	35 (1.4)	35 (1.3)	32 (1.2)	67 (2.6)	54 (2.2)	‡	13 (0.5)	22 (0.9)	‡	22 (0.9)	54 (2.1)
Average J-ring/slump diff., in	30 (1.2)		33 (1.3)		60 (2.4)		13 (0.5)		22 (0.9)		38 (1.5)	
T_{500} (T_{20}) J-ring, sec	1.1	†	2.0	†	†	†	‡	2.0	1.8	‡	3.8	†
L-box, H2/H1	‡	0.25	‡	0.29	‡	0	‡	0.46	0.40	‡	‡	0.40
Column segregation, % diff.	‡	-0.7	‡	7.4	1.8	‡	‡	1.7	9.5	‡	‡	7.9

† Spread did not reach 500 mm (20″)

‡ No measurement was made

Table 4.9 Summary of Fresh Concrete Test Results (continued)

Mix Description	**Mitchell Cast-In-Place**						**Mitchell Precast**					
W/C	**0.46**		**0.42**		**0.38**		**0.46**		**0.42**		**0.38**	
Batch ID	2	1	2	1	2	1	2	1	2	1	2	1
Temperature, °C (°F)	24.4 (76.0)	23.9 (75.0)	28.9 (84.0)	29.4 (85.0)	26.1 (79.0)	26.7 (80.0)	30.0 (86.0)	29.2 (84.5)	27.2 (81.0)	28.9 (84.0)	25.6 (78.0)	30.0 (86.0)
Unit weight, kN/m^3 (lb/ ft^3)	21.47 (136.7)	21.65 (137.8)	21.42 (136.4)	21.80 (138.8)	21.91 (139.4)	21.77 (138.5)	22.44 (142.6)	22.06 (140.4)	21.69 (138.1)	22.04 (140.3)	21.69 (138.1)	22.10 (140.6)
Air content, %	8.5	8.0	8.5	7.5	8.0	8.5	4.8	5.5	7.8	7.1	8.5	8.0
Slump spread, mm (in)	600 (23.6)	600 (23.6)	572 (22.5)	622 (24.5)	552 (21.8)	552 (21.8)	629 (24.8)	619 (24.4)	533 (21.0)	587 (23.1)	530 (20.9)	530 (20.9)
Average slump spread, mm (in)	600 (23.6)		597 (23.5)		552 (21.8)		624 (24.6)		560 (22.1)		530 (20.9)	
T$_{500}$ (T$_{20}$) slump, sec	0.59	0.87	1.04	0.89	2.26	1.89	0.84	0.89	2.14	1.36	3.04	2.87
VSI	0	0	0	0	0	0	0.5	0.5	0	0	0	0
J-ring spread, mm (in)	552 (21.8)	589 (23.2)	524 (20.6)	565 (22.3)	498 (19.6)	508 (20.0)	568 (22.4)	565 (22.3)	467 (18.4)	511 (20.1)	486 (19.1)	476 (18.8)
Average J-ring spread, mm (in)	571 (22.5)		545 (21.4)		503 (19.8)		567 (22.3)		489 (19.3)		481 (18.9)	
J-ring/slump spread difference, mm (in)	48 (1.8)	11 (0.4)	48 (1.9)	57 (2.2)	54 (2.2)	44 (1.8)	60 (2.4)	54 (2.1)	67 (2.6)	76 (3.0)	44 (1.8)	54 (2.1)
Average J-ring/slump diff., in	29 (1.2)		52 (2.1)		49 (1.9)		57 (2.3)		71 (2.8)		49 (1.9)	
T$_{500}$ (T$_{20}$) J-ring, sec	1.57	0.87	3.88	1.91	‡	5.3	1.73	1.97	‡	4.02	‡	‡
L-box, H2/H1	0.61	‡	0.55	‡	‡	0.46	0.82	‡	‡	0.49	‡	0.30
Column segregation, % diff.	‡	7.8	‡	17.4	- 6.9	‡	‡	- 1.2	4.0	‡	3.9	‡

† Spread did not reach 500 mm (20″)

‡ No measurement was made

4.4.1 Mix Temperature

The temperature of the SCC mixes was determined for each mix according to ASTM C 1064: “Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete” (ASTM 2006). The measured temperature values are presented in Table 4.9. The temperature of the concrete ranged from 23.3°C to 30.0°C (74°F to 86°F). These values are within the acceptable range of 10°C to 32°C (50°F to 90°F) stipulated in the South Dakota Standard Specification for Roads and Bridges (SD 2004).

4.4.2 Air Content

The air content of the SCC mixes was determined for each mix by means of a pressure air meter according to ASTM C 231: “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method” (ASTM 2006). The SCC was not rodded during filling of the measure. Air content measurements were made for every batch, resulting in two air content measurements for each mix tested in this study. The measured air contents are shown in Figures 4.10, 4.11, 4.12, and 4.13 for the R-PC, R-CIP, M-PC, and M-CIP mixes, respectively. The averaged measurements for all twelve mixes are shown in Figure 4.14.

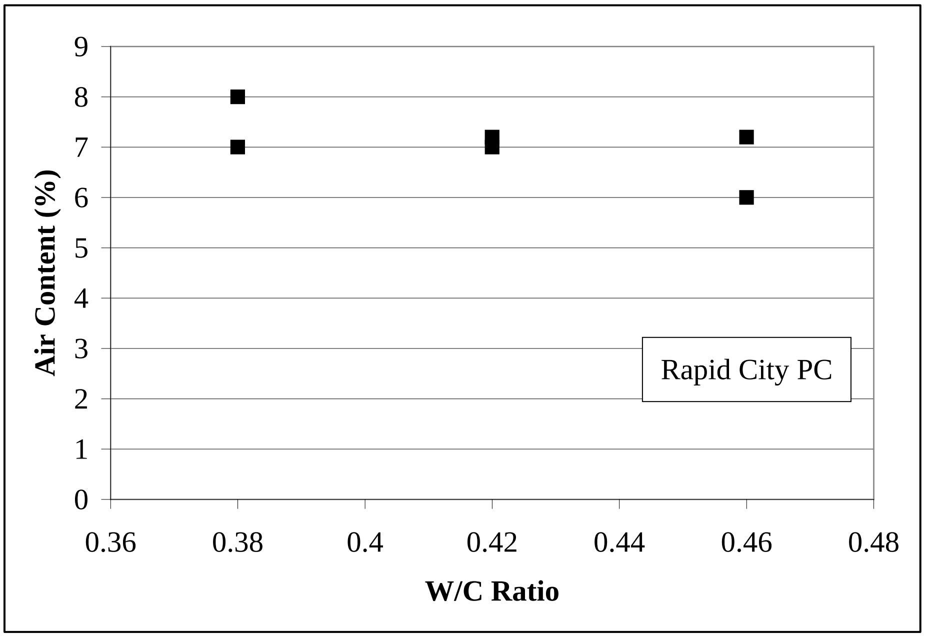


Figure 4.10 Air Content vs. W/C Ratio for Rapid City Precast Mix

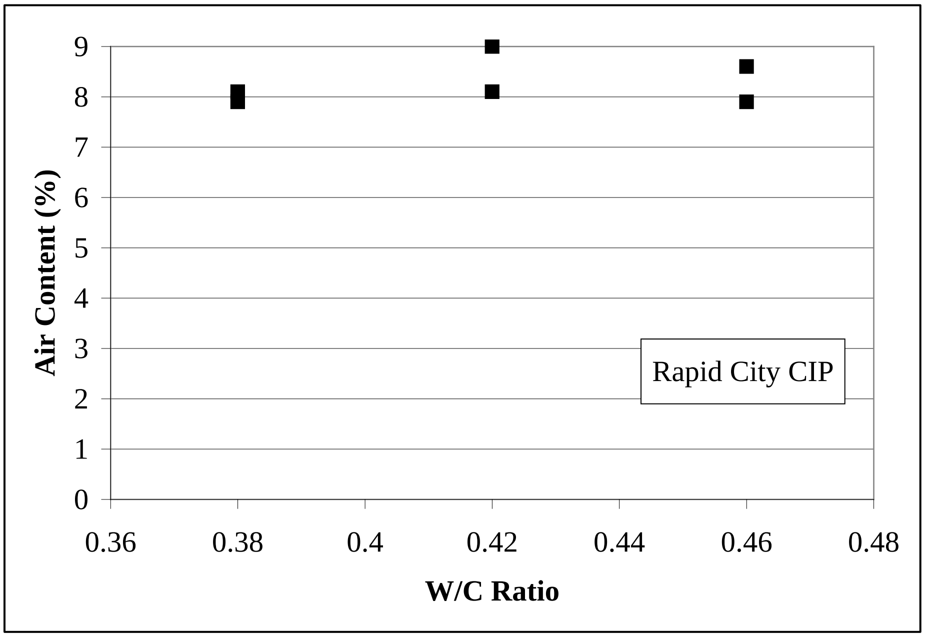


Figure 4.11 Air Content vs. W/C Ratio for Rapid City Cast-In-Place Mix

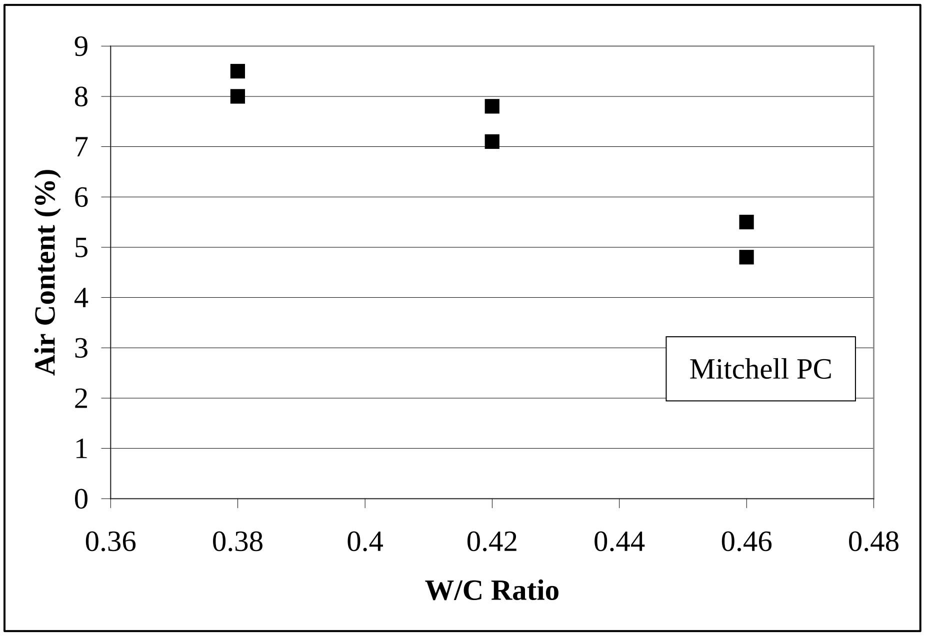


Figure 4.12 Air Content vs. W/C Ratio for Mitchell Precast Mix

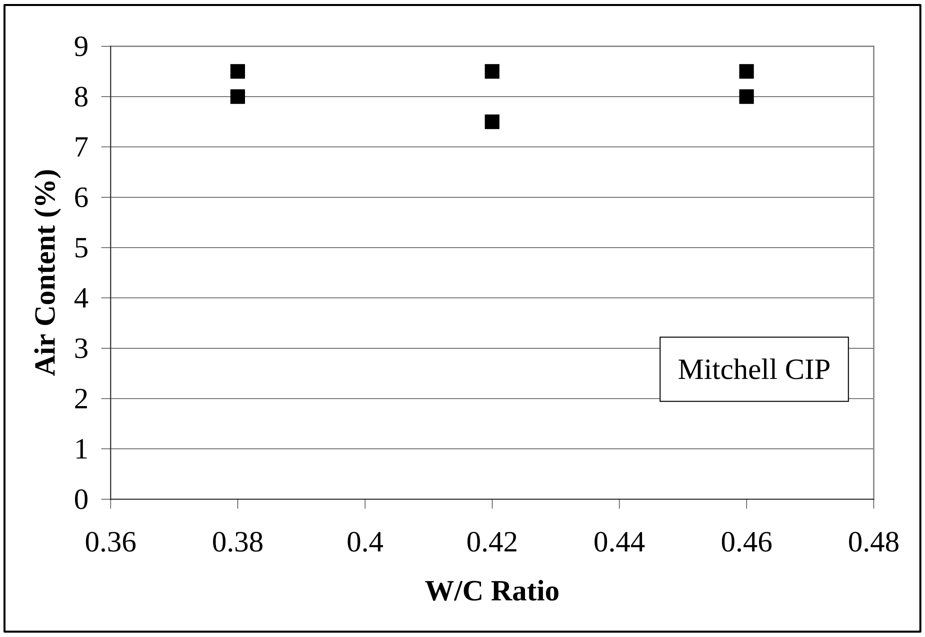


Figure 4.13 Air Content vs. W/C Ratio for Mitchell Cast-In-Place Mix

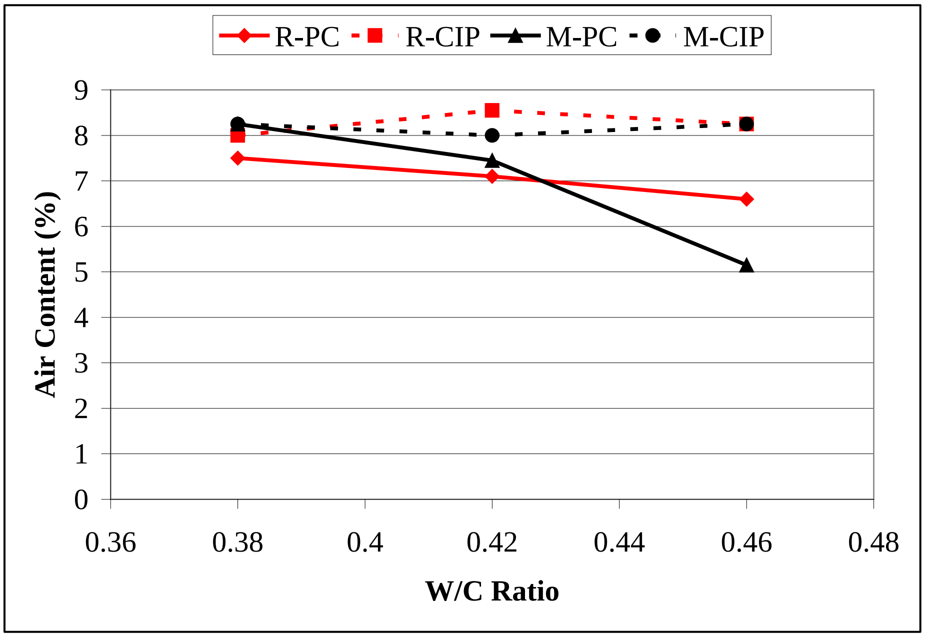


Figure 4.14 Air Content vs. W/C Ratio for All Mixes

The precast mixes exhibited a decrease in air content at higher w/c ratios. The cast-in-place mixes showed no significant variation in air content at different w/c ratios. The air content was higher, in general, for the cast-in-place than the precast mixes. The difference in the mixing time between the cast-in-place and the precast mixes could be the reason for the difference in the measured air content. The mixing time may have affected the chemical reactions or the amount of entrained and entrapped air in the mix.

The SDDOT specifies a target air content range of 5 to 7.5 percent (SD 2004; SD 2006). The air contents in the mixes were either within or higher than the target range. It should be noted that the air content can be adjusted by changing the amount of air entrainer used in each mix.

4.4.3 Slump Spread, T_{20}, and Visual Stability Index (VSI)

The slump spread of each mix was determined according to ASTM C 1611 (ASTM 2006). Two batches of each of the twelve mix designs were made and tested for slump, T_{20}, and visual stability index (VSI). The values of slump spread and T_{20} were averaged for each mix design. The average slump spread values are shown in Figures 4.15, 4.16, 4.17, and 4.18 for the R-PC, R-CIP, M-PC, and M-CIP, respectively. Figure 4.19 shows a summary of the slump spread for all mixes.

The results show that as w/c ratio increases, the slump spread increases even though the HRWR admixture quantity is reduced with increasing w/c ratio. Therefore, controlling the w/c ratio in SCC is critical for achieving the desired slump spread.

The measured range of slump spread values in this study varied between 489 mm (19.25 in.) and 629 mm (24.75 in.). There are no universally accepted standard values for minimum and maximum slump spread values for a mix to qualify as SCC. Normally, slump spread is specified to meet project- or application-specific performance criteria. Minimum specified slump spread values reported in the literature vary between 500 mm (20 in.) (Georgia 2005) and 650 mm (26 in.) (Nowak 2005) whereas the maximum specified slump spread values reported in the literature vary between 750 mm (30 in.) to 800 (32 in.) (NC 2005; Nowak 2005). The measured slump values in this study were in the low range of the reported slump values for SCC.

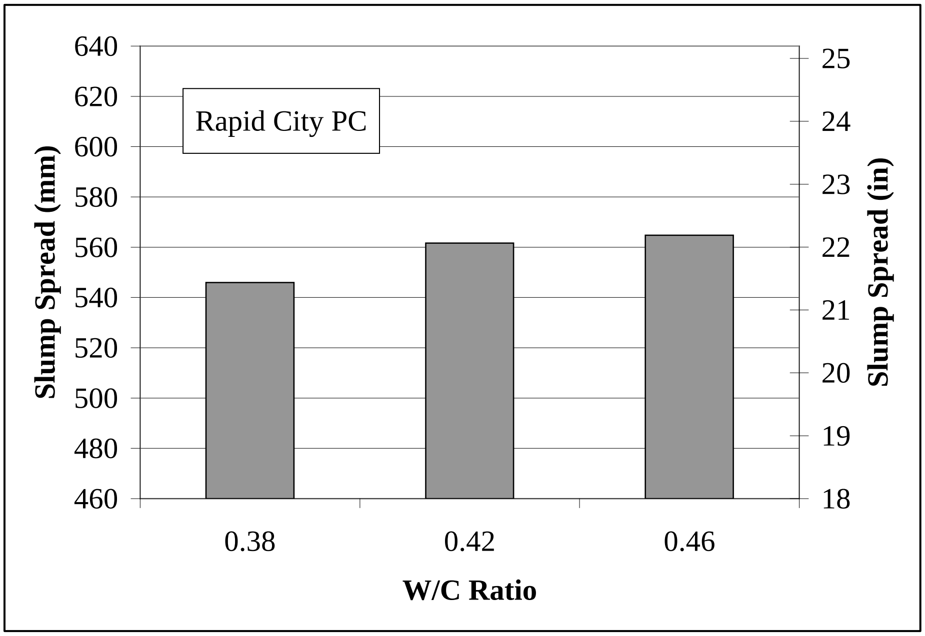


Figure 4.15 Slump Spread vs. W/C Ratio for Rapid City Precast Mix

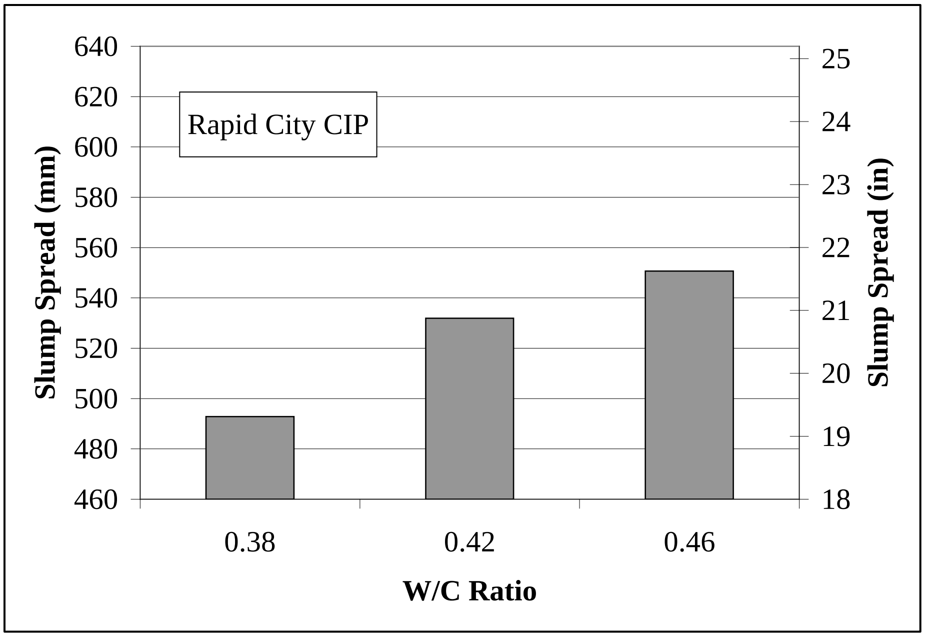


Figure 4.16 Slump Spread vs. W/C Ratio for Rapid City Cast-In-Place Mix

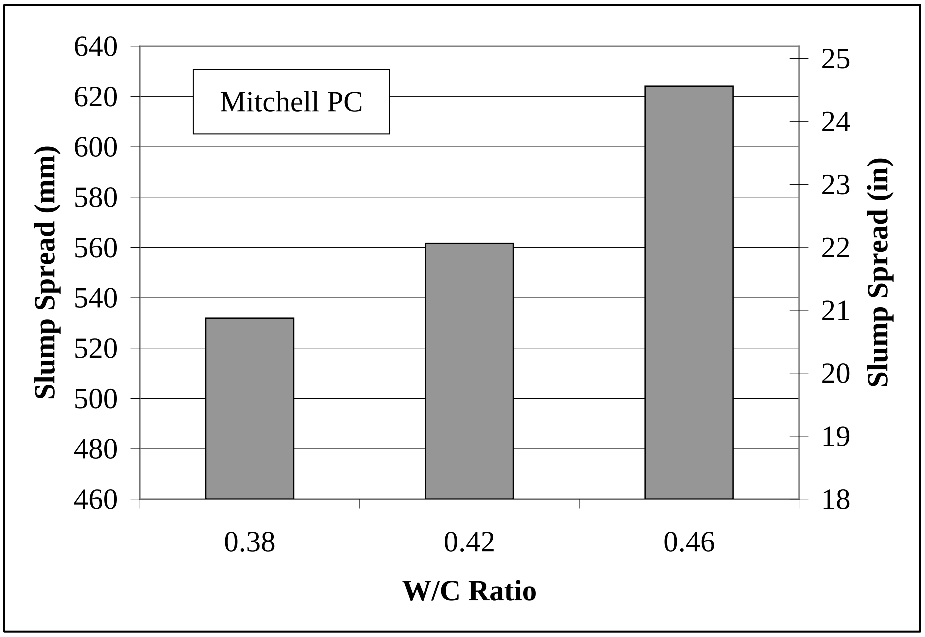


Figure 4.17 Slump Spread vs. W/C Ratio for Mitchell Precast Mix

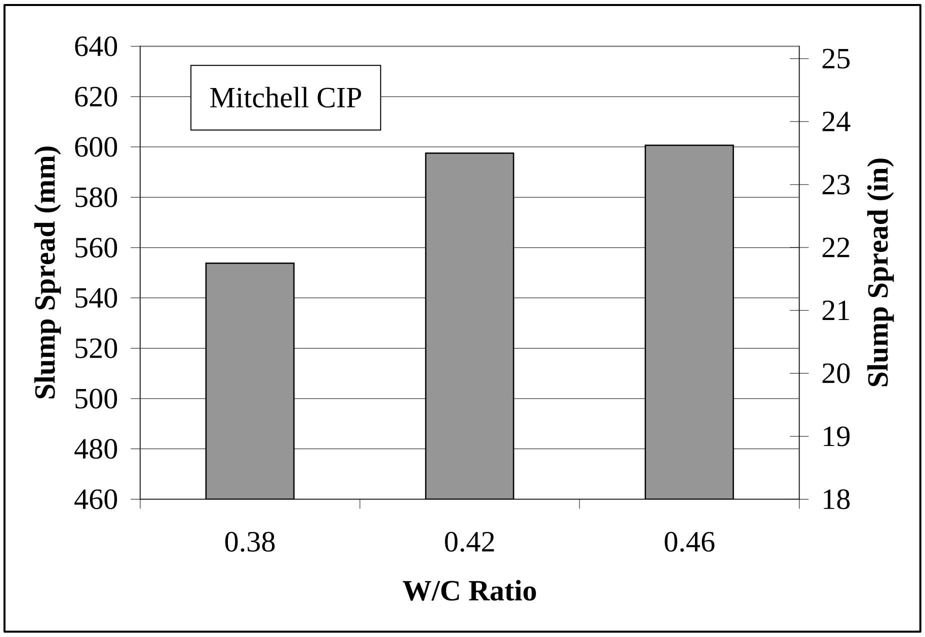


Figure 4.18 Slump Spread vs. W/C Ratio for Mitchell Cast-In-Place Mix

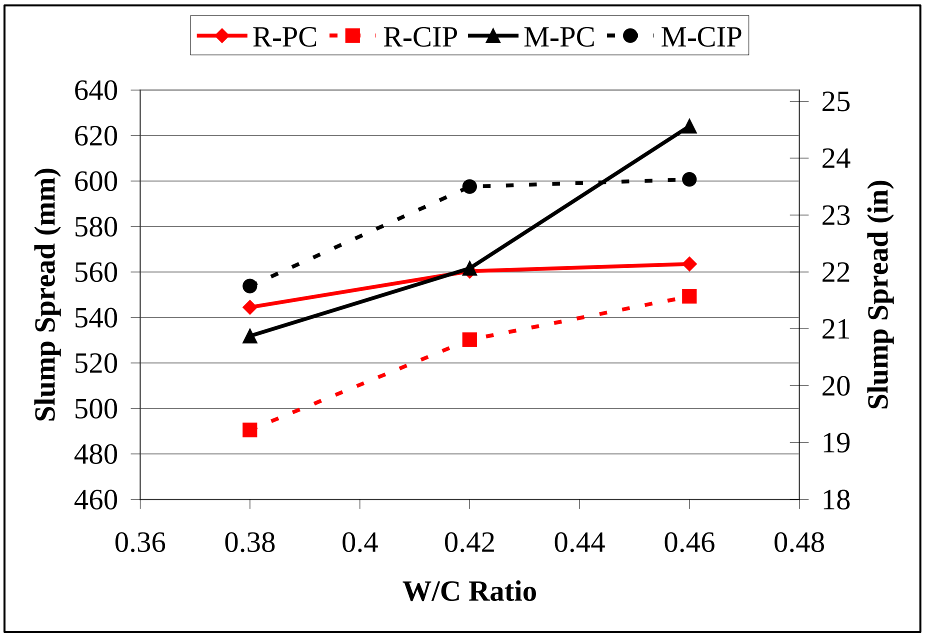


Figure 4.19 Slump Spread vs. W/C Ratio for All Mixes

During the slump flow tests, the time for the concrete to cross the 20 inch (approximately 500 mm) diameter circle, T_{20}, was determined using a stopwatch. The average values of T_{20} for each mix design are shown in Figures 4.20, 4.21, 4.22, and 4.23. The average T_{20} values for all mix designs are shown in Figure 4.24. The figures show that as w/c ratio increases, the time for the slump spread to reach 20 inch diameter decreases.

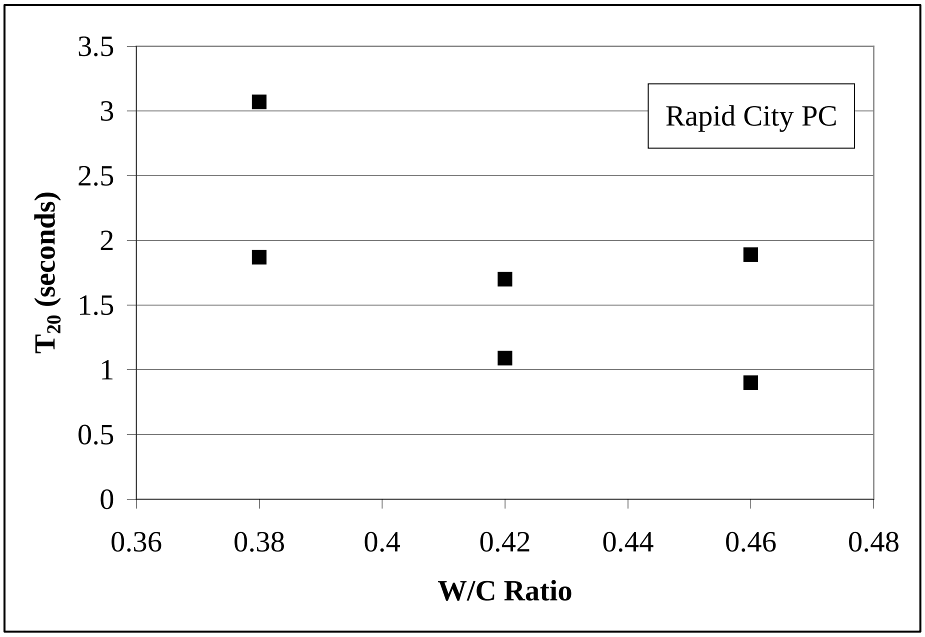
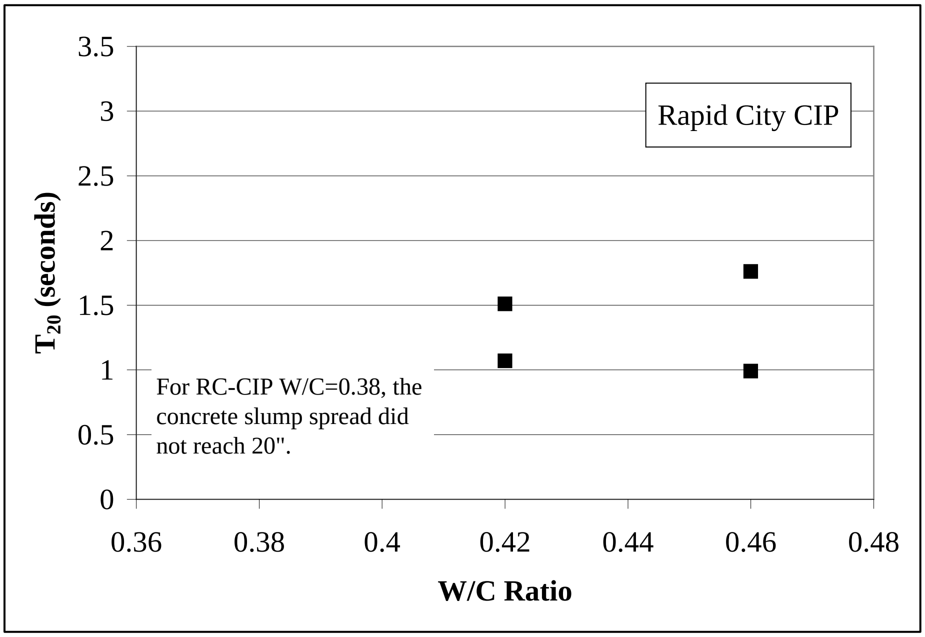


Figure 4.20 T$_{20}$ vs. W/C Ratio for Rapid City Precast Mix



For RC-CIP W/C=0.38, the concrete slump spread did not reach 20".

Figure 4.21 T$_{20}$ vs. W/C Ratio for Rapid City Cast-In-Place Mix

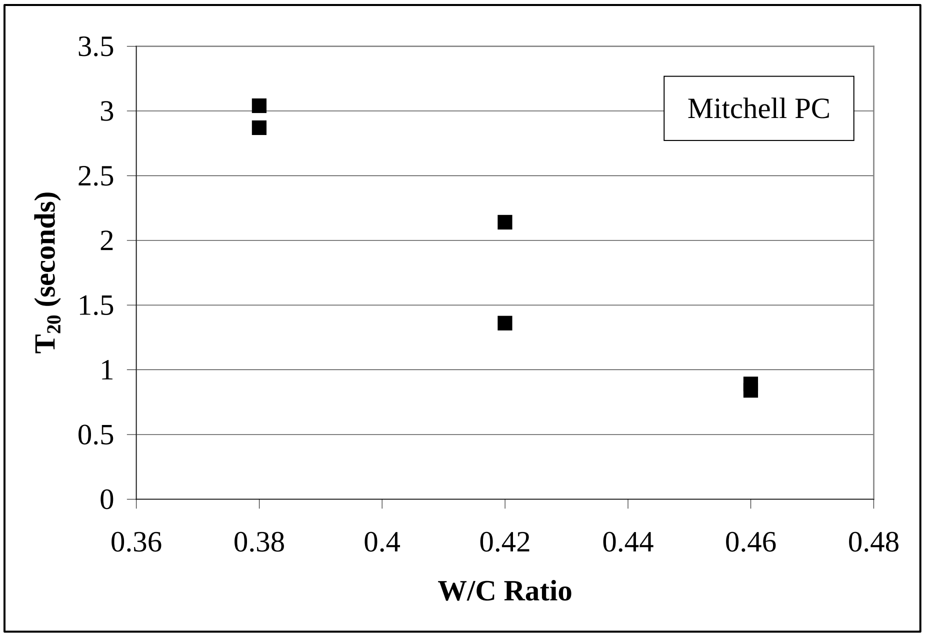


Figure 4.22 T_{20} vs. W/C Ratio for Mitchell Precast Mix

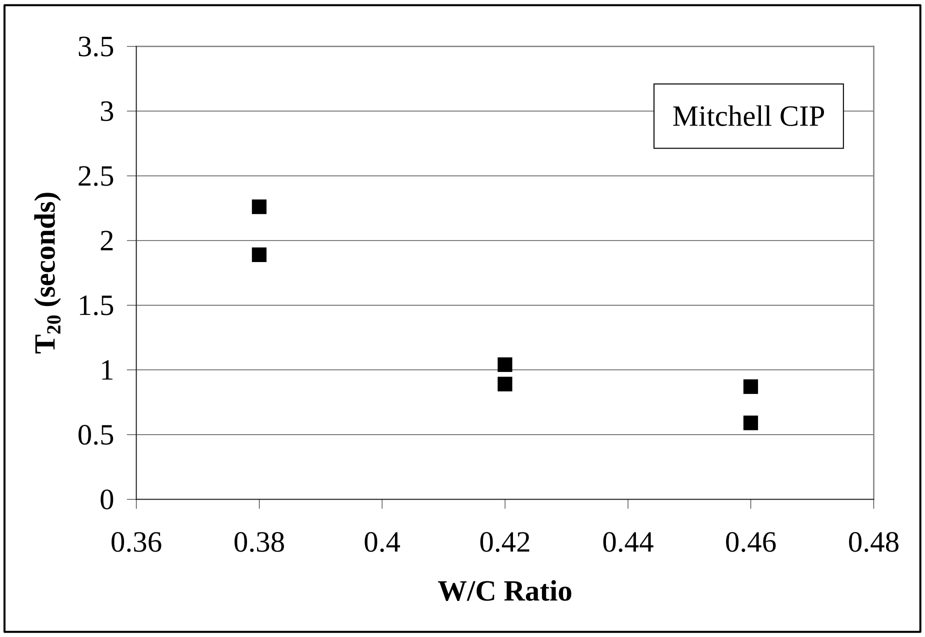


Figure 4.23 T_{20} vs. W/C Ratio for Mitchell Cast-In-Place Mix

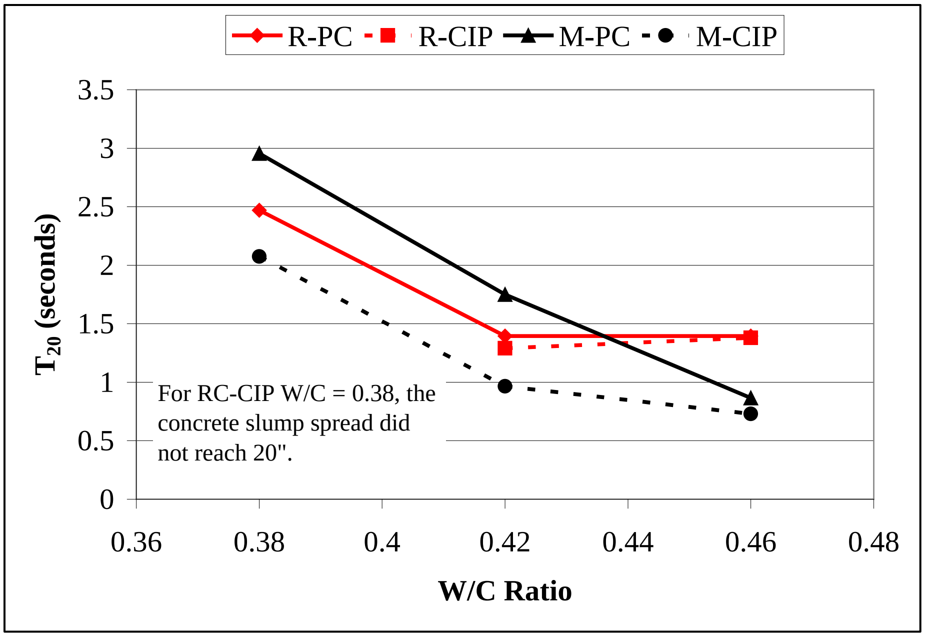


Figure 4.24 T_{20} vs. W/C Ratio for All Mixes

The measured T_{20} values ranged between 0.6 seconds to 3.0 seconds. Reported acceptable values for T_{20} vary between 2 to 8 seconds (Nowak 2005, Georgia). The values for T_{20} in this study were lower than normally reported in the literature. However, all the mixes prepared in this study were stable even at low T_{20} values. It appears that low T_{20} values have no significant implications on the stability or robustness of the SCC mix.

The R-CIP mix with a w/c ratio of 0.38 was not flowable enough to reach a slump spread diameter of 500 mm (20 inches) in either batch. For this reason, there was no T_{20} value measured for this mix.

The visual stability index (VSI), as described in ASTM C 1611, was evaluated and recorded during the slump flow tests. The VSI values for all mixes are shown in Table 4.9. The observed VSI values were either 0.5 or 0. It should be noted that the VSI evaluation was performed under laboratory conditions. According to ASTM C 1611, the observed VSI values in this study indicate that the mixes were stable to highly stable.

4.4.4 J-Ring Spread

The slump spread of each mix when flowing through a J-ring was determined according to ASTM C 1621. The susceptibility of the mix to blocking in areas of congested steel reinforcement is determined by comparing the spread in the J-ring test to the spread in the slump spread test. The measured spread difference between the J-ring and the slump spread tests is shown in Figures 4.25, 4.26, 4.27, and 4.28 for the R-PC, R-CIP, M-CP, and M-CIP, respectively. A summary of all the measured spread difference values is shown in Figure 4.29. A larger difference value indicates a higher level of blocking. The measured data show that as W/C ratio increases, the level of blocking usually decreases.

According to ASTM C 1621 (ASTM 2006), blocking assessment is related to the difference between slump flow and J-ring spread. For a difference of up to 25 mm (1 in), the mix is determined to have “No Visible Blocking.” For a difference greater than 25 mm (1 in) but no more than 50 mm (2 in), the mix is determined to have “Minimal to Noticeable Blocking.” For a difference greater than 50 mm (2 in), the mix is determined to have “Noticeable to Extreme Blocking.” The measured difference of slump spread diameter and J-ring spread diameter ranged from 13 to 76 mm (0.5 to 3.0 in). The R-PC mix exhibited the least potential to blocking while the M-PC exhibited the highest potential to blocking. Except for the M-PC mix, most of the values indicate "No Visible Blocking" to "Minimal to Noticeable Blocking."

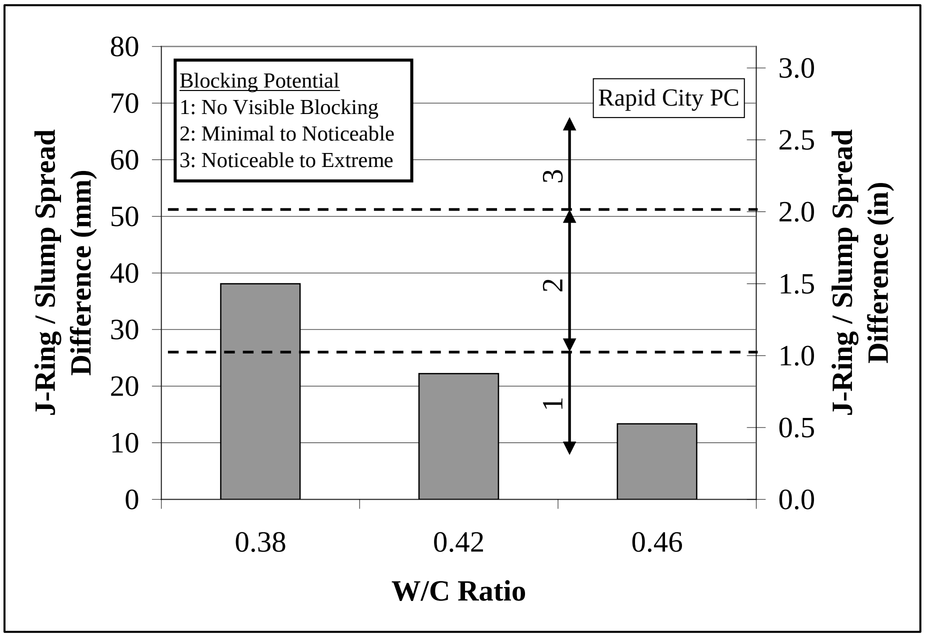


Figure 4.25 J-Ring Blocking vs. W/C Ratio for Rapid City Precast Mix

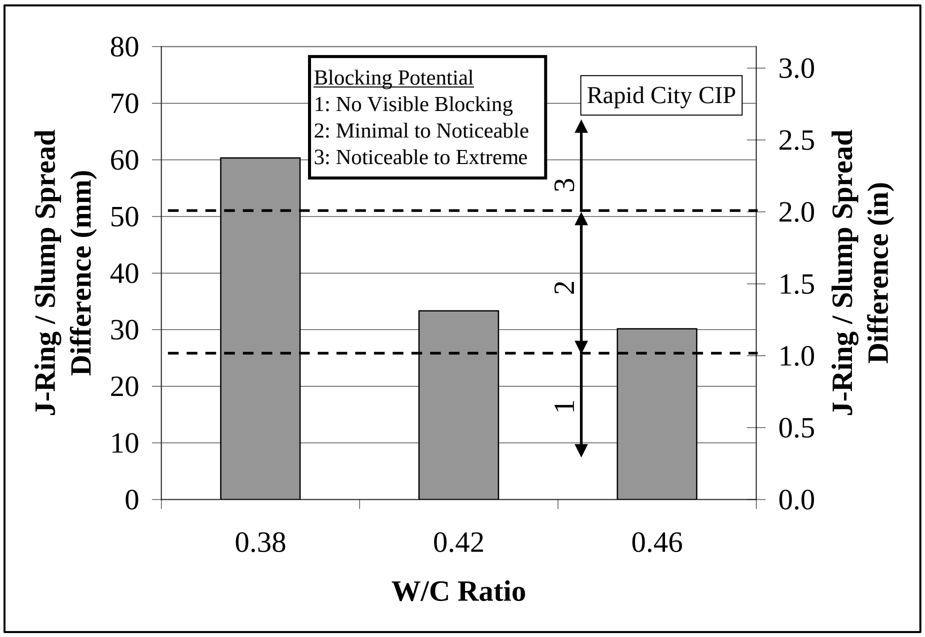


Figure 4.26 J-Ring Blocking vs. W/C Ratio for Rapid City Cast-In-Place Mix

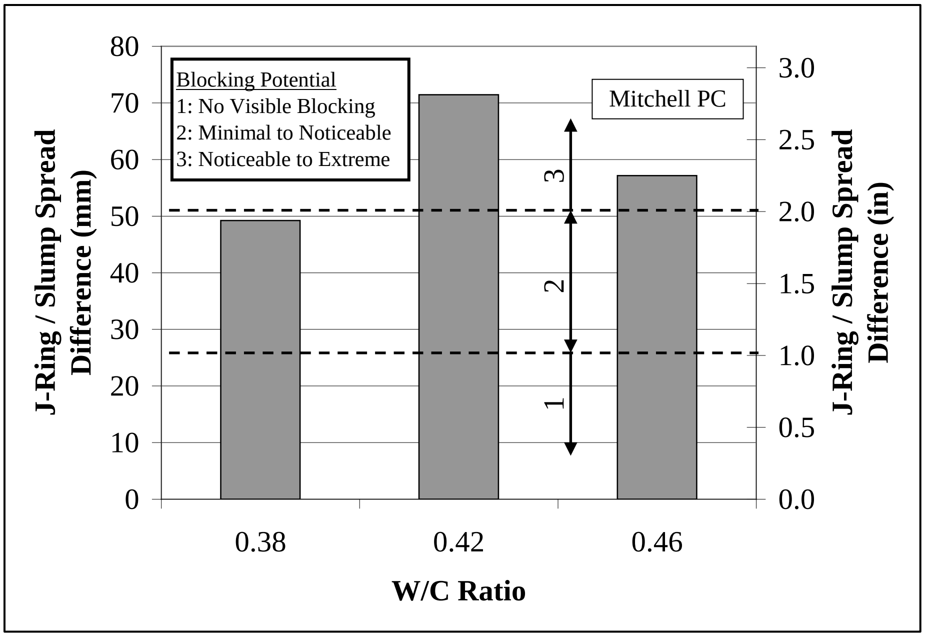


Figure 4.27 J-Ring Blocking vs. W/C Ratio for Mitchell Precast Mix

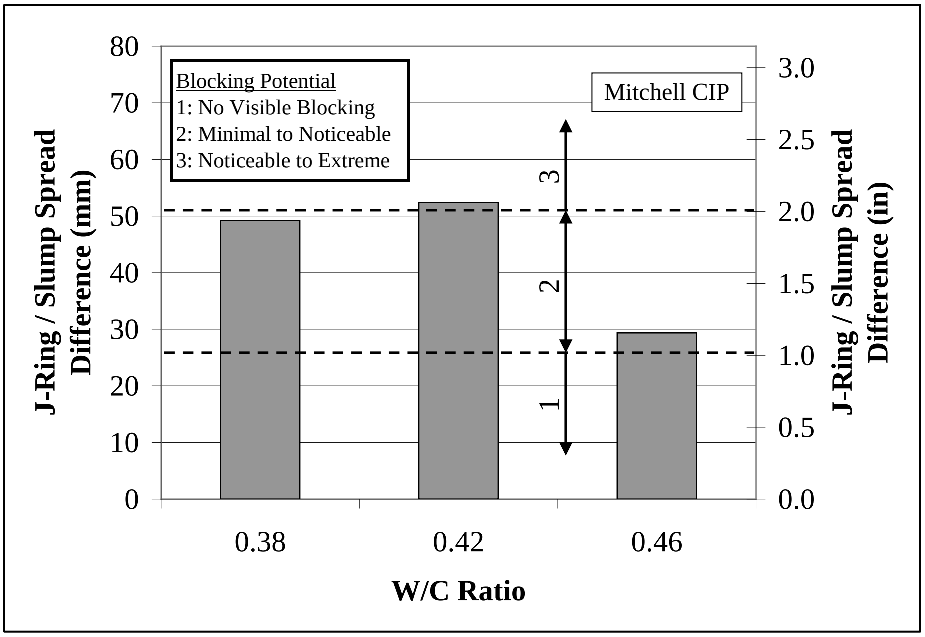


Figure 4.28 J-Ring Blocking vs. W/C Ratio for Mitchell Cast-In-Place Mix

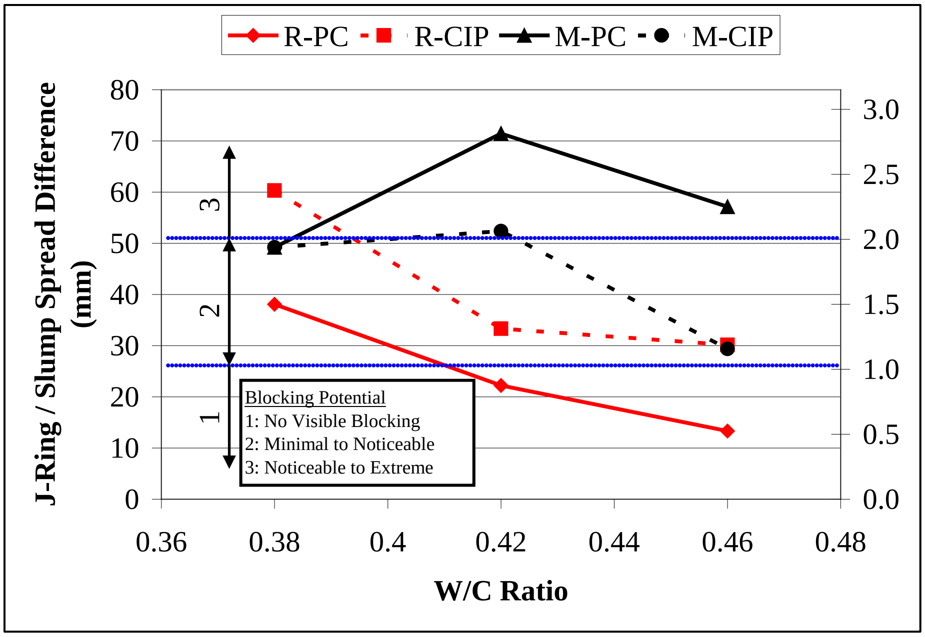


Figure 4.29 J-Ring Blocking vs. W/C Ratio for All Mixes

4.4.5 L-Box Blocking Ratio

The L-box test was performed to assess blocking potential in narrow formwork and around tight corners. A blocking ratio H2/H1, as described in Section 3.2.6, was determined for each mix. The H2/H1 ratios versus the w/c values for mixes R-PC, R-CIP, M-PC, and M-CIP are shown in Figures 4.30, 4.31, 4.32, and 7.33, respectively. A larger H2/H1 value indicates a lower potential for blocking. Figure 4.34 is a summary of Figures 4.30 through 4.33. The figure indicates that as the w/c ratio increases, the value of H2/H1 increases and the amount of blocking decreases. This followed the same blocking trend indicated by the J-ring spread and slump spread difference.

There is no standard H2/H1 value that is used for acceptance of SCC. However, the European Federation of Specialist Construction Chemicals and Concrete Systems (EFNARC) suggest a typical range of H2/H1 of 0.8 to 1.0 (EFNARC 2002). The values of H2/H1 in this study ranged from 0.0 to 0.82. Most of the H2/H1 values were less than 0.8. The measured H2/H1 appears to indicate a high blocking potential. The H2/H1 values may be low not because of the amount of blocking only, but also because of low flowability. For thin elements such as box culvert walls, the Mitchell mixes with w/c of 0.46 tested in this study appear to provide the appropriate flowability characteristics with adequate concrete strength. The blocking potential of all of the Rapid City mixes may have to be reduced if such mixes are to be used for casting thin and intricate elements.

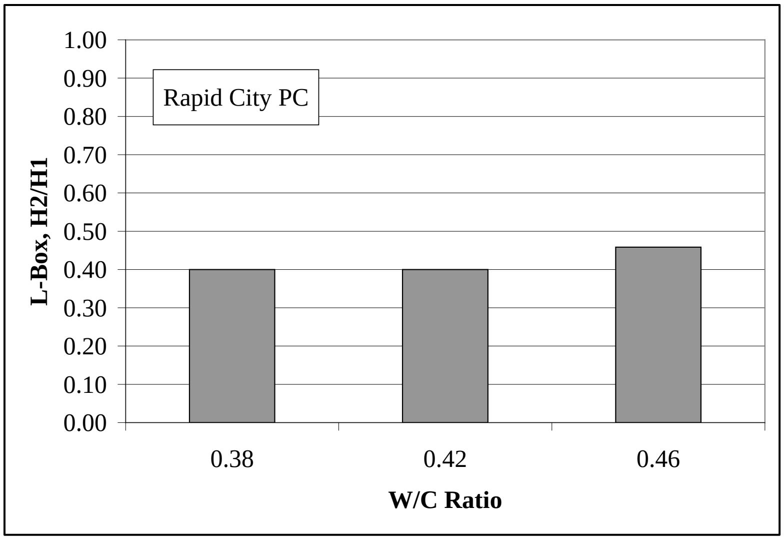
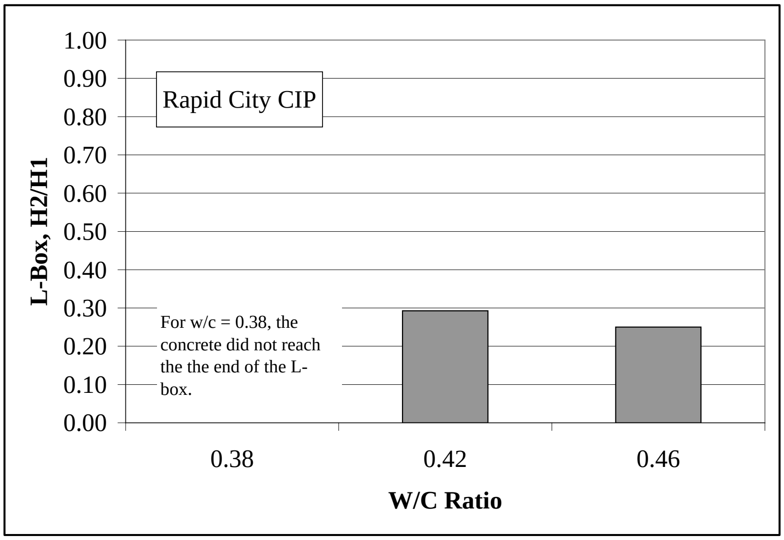


Figure 4.30 L-Box H2/H1 vs. W/C Ratio for Rapid City Precast Mix



For w/c = 0.38, the concrete did not reach the the end of the L-box.

Figure 4.31 L-Box H2/H1 vs. W/C Ratio for Rapid City Cast-In-Place Mix

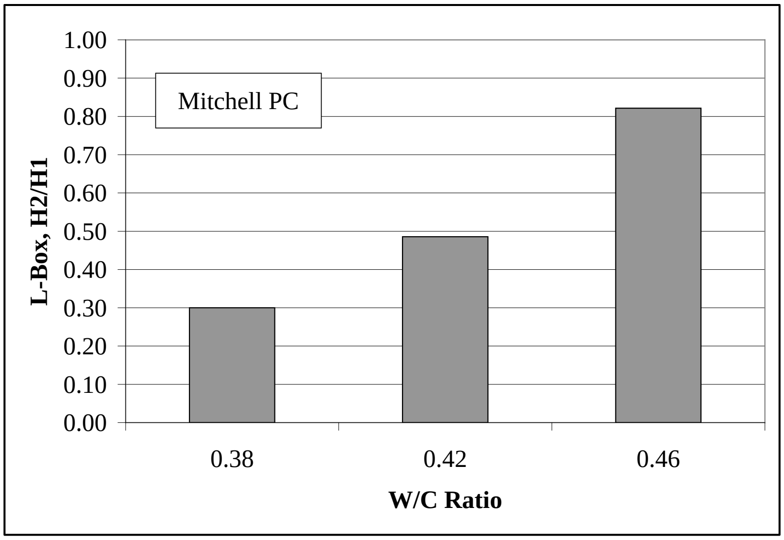


Figure 4.32 L-Box H2/H1 vs. W/C Ratio for Mitchell Precast Mix

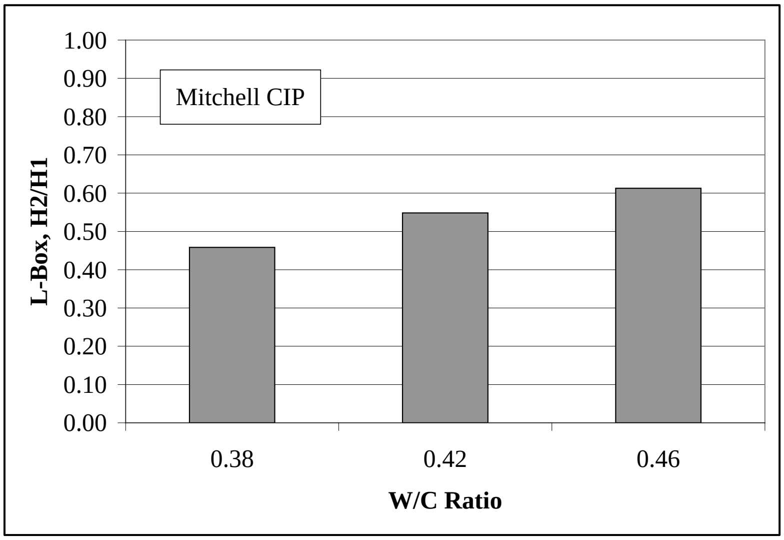


Figure 4.33 L-Box H2/H1 vs. W/C Ratio for Mitchell Cast-In-Place

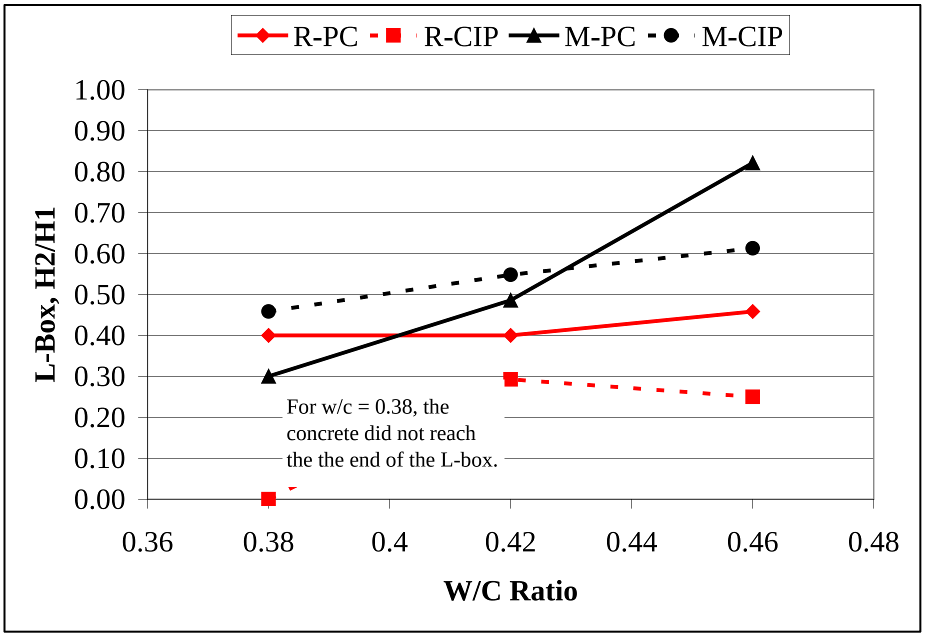


Figure 4.34 L-Box H2/H1 vs. W/C Ratio for Mitchell Cast-In-Place

4.4.6 Column Segregation

The column segregation test was performed for each mix design to assess segregation. The column segregation test was not an ASTM standard at the time of testing (summer 2006), but was later approved as ASTM C 1610: "Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique" (ASTM 2006). The percent difference in coarse aggregate (retained on No. 4 sieve) between the bottom and top column segments was measured. The measured percent difference values are shown in Figure 4.35.

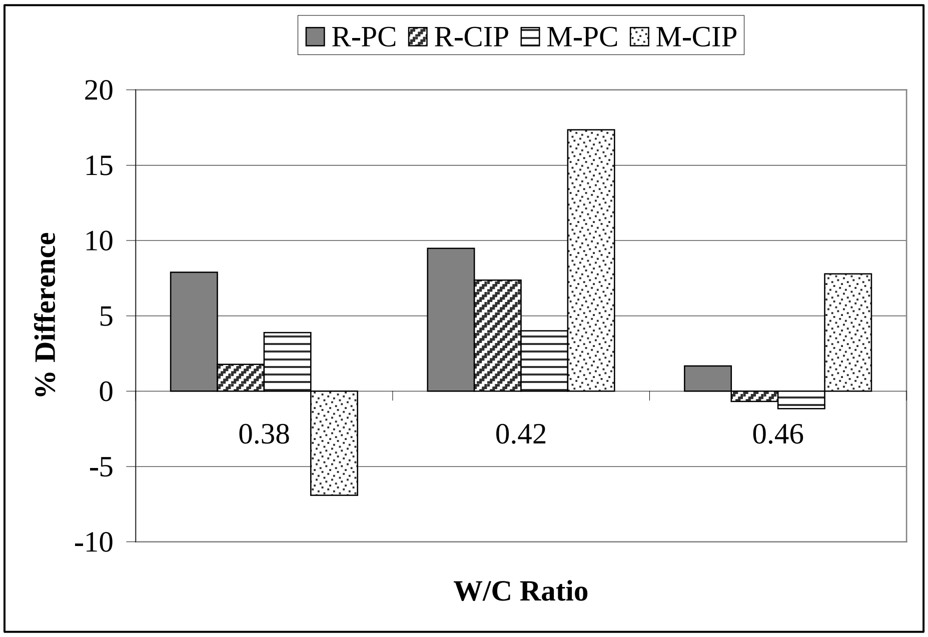


Figure 4.35 Column Segregation % Difference vs. W/C Ratio for All Mixes

The percent difference in coarse aggregate between the top and the bottom section ranged from -6.9% to 7.8%, with one extreme value of 17.4%. A negative percent difference indicates that the column bottom segment has less coarse aggregate than the column top segment. According to ASTM C 1610, when the amount of coarse aggregate in the top section is more than that in the bottom section, segregation is considered to be 0% (no measured segregation).

There are no standard values of segregation for acceptance of SCC. In one study, column segregation values of up to 5.6% were recorded (Assaad 2004). The concrete mixes in this study were found to be stable by both the VSI and the HVSI (Section 3.5.5) methods. The measured high value of 17.4% is an anomaly that may have been the result of improper sampling. The results in Figure 4.35 also do not show a specific trend. The mixes with w/c of 0.46 had the highest flowability, yet the column segregation test results indicate that those mixes exhibited the least segregation, contrary to expected behavior. Therefore, it appears that the column segregation test values are better suited for qualitative and comparative purposes.

4.5 Hardened Concrete Testing and Results

The tests performed to evaluate the hardened properties of the SCC were ASTM C 39: “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,” ASTM C 78: “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading),” ASTM C 496: “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens” (ASTM 2006), and AASHTO draft “Standard Method of Test for Static Segregation of Hardened Self-Consolidating Concrete Cylinders” (AASHTO 2005). The results of the hardened concrete tests are presented in this section. A summary of the results of these tests is presented in Table 4.10. A blank space indicates that the test was not performed.

Table 4.10 Hardened Concrete Test Results

Mix Description	**Rapid City Cast-In-Place**						**Rapid City Precast**					
W/C	**0.46**		**0.42**		**0.38**		**0.46**		**0.42**		**0.38**	
Batch	2	1	2	1	2	1	2	1	2	1	2	1
7-Day Comp. Strength, MPa (psi)	33.8 (4898)	33.9 (4916)	34.4 (4987)	35.0 (5075)	45.4 (6578)	42.7 (6189)	34.8 (5040)	34.9 (5058)	36.3 (5270)	39.5 (5730)	42.4 (6154)	41.7 (6048)
	†	32.7 (4739)	34.9 (5058)	†	†	46.2 (6702)	37.3 (5411)	†	38.5 (5588)	37.2 (5394)	42.2 (6119)	†
Average 7-Day Batch Comp. Strength, MPa (psi)	33.8 (4898)	33.3 (4828)	34.6 (5022)	35.0 (5075)	45.4 (6578)	44.4 (6446)	36.0 (5226)	34.9 (5058)	37.4 (5429)	38.4 (5562)	42.3 (6136)	41.7 (6048)
Average 7-Day Mix Comp. Strength, MPa (psi)	33.5 (4851)		34.8 (5040)		44.8 (6490)		35.6 (5170)		37.9 (5495)		42.1 (6107)	
28-Day Comp. Strength, MPa (psi)	42.7 (6189)	41.3 (5995)	41.8 (6066)	42.8 (6207)	52.4 (7604)	53.5 (7763)	46.1 (6685)	44.8 (6490)	44.5 (6455)	50.5 (7321)	49.8 (7215)	50.1 (7268)
	†	41.2 (5977)	41.8 (6066)	43.4 (6295)	48.9 (7091)	56.2 (8152)	46.6 (6755)	45.0 (6525)	†	47.7 (6914)	52.4 (7604)	50.7 (7356)
	†	†	†	†	†	†	45.7 (6623)	†	†	48.4 (7021)	49.0 (7109)	†
Average 28-Day Batch Comp. Strength, MPa (psi)	42.7 (6189)	41.3 (5986)	41.8 (6066)	43.1 (6251)	50.7 (7348)	54.9 (7958)	46.1 (6687)	44.9 (6508)	44.5 (6455)	48.9 (7085)	50.4 (7309)	50.4 (7312)
Average 28-Day Mix Comp. Strength, MPa (psi)	47.1 (6054)		42.5 (6158)		52.8 (7653)		45.6 (6616)		47.8 (6928)		50.4 (7311)	

† No measurement was made

Table 4.10 Hardened Concrete Test Results (Continued)

Mix Description	**Rapid City Cast-In-Place**						**Rapid City Precast**					
W/C	0.46		0.42		0.38		0.46		0.42		0.38	
Batch	2	1	2	1	2	1	2	1	2	1	2	1
Splitting Tensile Strength, MPa (psi)	3.63 (526)	3.35 (486)	4.18 (606)	3.35 (486)	4.27 (619)	4.08 (592)	3.19 (462)	4.57 (663)	4.76 (690)	3.66 (531)	4.15 (601)	5.06 (734)
	3.23 (469)	†	†	†	†	4.47 (648)	3.84 (557)	†	†	†	3.90 (566)	†
Average Batch Splitting Tensile Strength, MPa (psi)	3.43 (497)	3.35 (486)	4.18 (606)	3.35 (486)	4.27 (619)	4.28 (620)	3.51 (510)	4.57 (663)	4.76 (690)	3.66 (531)	4.02 (584)	5.06 (734)
Average Mix Splitting Tensile Strength, MPa (psi)	3.40 (494)		3.76 (546)		4.27 (620)		3.87 (561)		4.21 (610)		4.37 (634)	
Modulus of Rupture, MPa (psi)	4.02 (583)	†	4.27 (619)	4.26 (618)	4.65 (575)	4.79 (694)	†	5.08 (736)	4.88 (708)	4.98 (722)	4.98 (722)	4.79 (694)
	4.64 (674)	†	†	†	†	†	†	†	†	†	†	†
Average Modulus of Rupture, MPa (psi)	4.33 (628)		4.27 (619)		4.72 (685)		5.08 (736)		4.93 (715)		4.88 (708)	
HVSI	0	†	0	†	0	†	0	†	†	0	0	†

† No measurement was made

Table 4.10 Hardened Concrete Test Results (Continued)

Mix Description	**Mitchell Cast-In-Place**						**Mitchell Precast**					
W/C	**0.46**		**0.42**		**0.38**		**0.46**		**0.42**		**0.38**	
Batch	2	1	2	1	2	1	2	1	2	1	2	1
7-Day Comp. Strength, MPa (psi)	31.2 (4527)	31.7 (4598)	36.5 (5287)	38.3 (5553)	42.6 (6172)	39.8 (5765)	33.2 (4810)	35.8 (5199)	36.0 (5217)	38.0 (5517)	39.4 (5712)	35.8 (5199)
	31.6 (4580)	†	38.2 (5535)	†	†	40.0 (5800)	35.4 (5128)	†	†	38.3 (5535)	36.0 (5217)	38.9 (5641)
Average 7-Day Batch Comp. Strength, MPa (psi)	31.4 (4554)	31.7 (4598)	37.3 (5411)	38.3 (5553)	42.6 (6172)	39.9 (5783)	34.3 (4969)	35.8 (5199)	36.0 (5217)	38.2 (5535)	37.7 (5464)	37.4 (5420)
Average 7-Day Mix Comp. Strength, MPa (psi)	31.5 (4568)		37.6 (5458)		40.8 (5912)		34.8 (5046)		37.4 (5429)		37.5 (5442)	
28-Day Comp. Strength, MPa (psi)	39.4 (5712)	40.6 (5889)	43.9 (6366)	44.0 (6384)	50.8 (7374)	46.6 (6755)	45.6 (6614)	44.6 (6472)	43.9 (6366)	45.6 (6614)	49.5 (7180)	50.2 (7286)
	41.5 (6013)	41.5 (6013)	44.1 (6402)	46.1 (6685)	52.4 (7604)	52.7 (7639)	45.2 (6561)	46.1 (6685)	43.5 (6313	47.8 (6932)	47.6 (6897)	49.0 (7109)
	39.6 (5747)	†	47.3 (6861)	†	†	†	†	†	†	†	†	†
Average 28-Day Batch Comp. Strength, MPa (psi)	40.2 (5824)	41.0 (5951)	45.1 (6543)	45.1 (6543)	51.6 (7197)	49.6 (7197)	45.4 (6587)	45.4 (6878)	43.7 (6340)	46.7 (6773)	48.5 (7038)	49.6 (7197)
Average 28-Day Mix Comp. Strength, MPa (psi)	40.5 (5875)		45.1 (6539)		50.6 (7343)		45.4 (6583)		45.2 (6556)		49.1 (7118)	

† No measurement was made

Table 4.10 Hardened Concrete Test Results (Continued)

Mix Description	**Mitchell Cast-In-Place**						**Mitchell Precast**					
W/C	**0.46**		**0.42**		**0.38**		**0.46**		**0.42**		**0.38**	
Batch	2	1	2	1	2	1	2	1	2	1	2	1
Splitting Tensile Strength, MPa (psi)	3.02 (438)	3.51 (5.08)	3.75 (544)	3.90 (566)	4.33 (628)	4.33 (628)	3.81 (553)	2.96 (429)	4.12 (597)	4.24 (615)	4.12 (597)	4.48 (650)
	3.54 (513)	†	3.90 (566)	†	†	4.12 (597)	3.84 (557)	†	†	3.75 (544)	†	†
Average Batch Splitting Tensile Strength, MPa (psi)	3.28 (475)	3.51 (508)	3.83 (555)	3.90 (566)	4.33 (628)	4.22 (612)	3.83 (555)	2.96 (429)	4.12 (697)	3.99 (579)	4.12 (597)	4.48 (650)
Average Mix Splitting Tensile Strength, MPa (psi)	3.35 (486)		3.85 (559)		4.26 (617)		3.54 (513)		4.03 (585)		4.30 (623)	
Modulus of Rupture, MPa (psi)	3.75 (544)	3.72 (539)	3.72 (539)	4.10 (594)	4.14 (600)	4.02 (583)	3.72 (539)	3.79 (550)	3.83 (556)	3.79 (550)	4.54 (658)	4.44 (644)
Average Modulus of Rupture, MPa (psi)	3.73 (542)		3.91 (567)		4.08 (592)		3.75 (544)		3.81 (553)		4.49 (651)	
HVSI	0	†	†	0	†	0	0	†	0	†	†	0

† No measurement was made

4.5.1 7-Day Compressive Strength

Standard 6″ x 12″ concrete cylinders were tested according to ASTM C 39: "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" (ASTM 2006) after curing for seven days. Several cylinders from each mix were tested and the average compressive strength values were calculated. The test results are presented in Table 4.10. The average values for 7-day compressive strength are shown in Figures 4.36, 4.37, 4.38, and 4.39, for mixes R-PC, R-CIP, M-PC, and M-CIP, respectively and summarized in Figure 4.40. The results show that the w/c ratio had a significant effect on all mixes. As the w/c ratio was increased, the 7-day compressive strength of the SCC decreased for all mixes. Decreasing strength with increasing w/c was expected. This follows the trend established for SCC, as well as the established trend for conventional concrete (Mindess 2003).

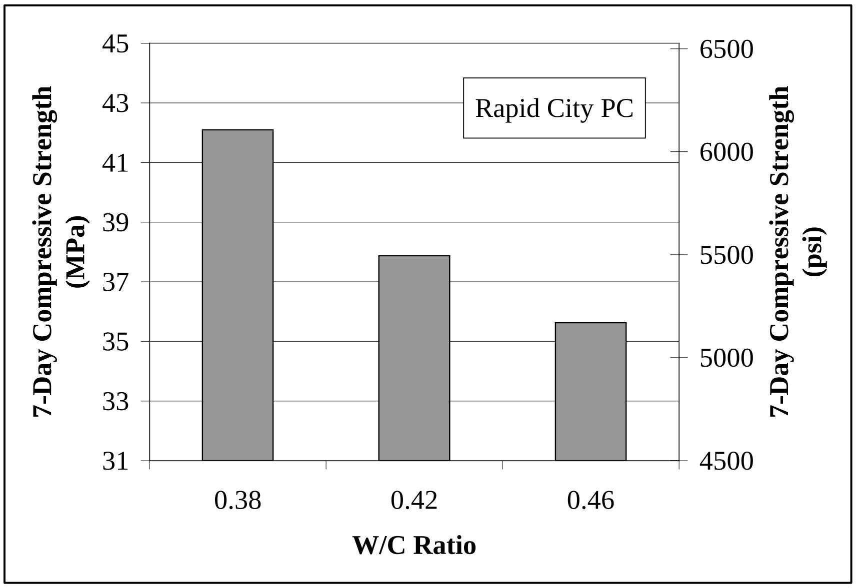


Figure 4.36 7-Day Compressive Strength vs. W/C Ratio for Rapid City Precast Mix

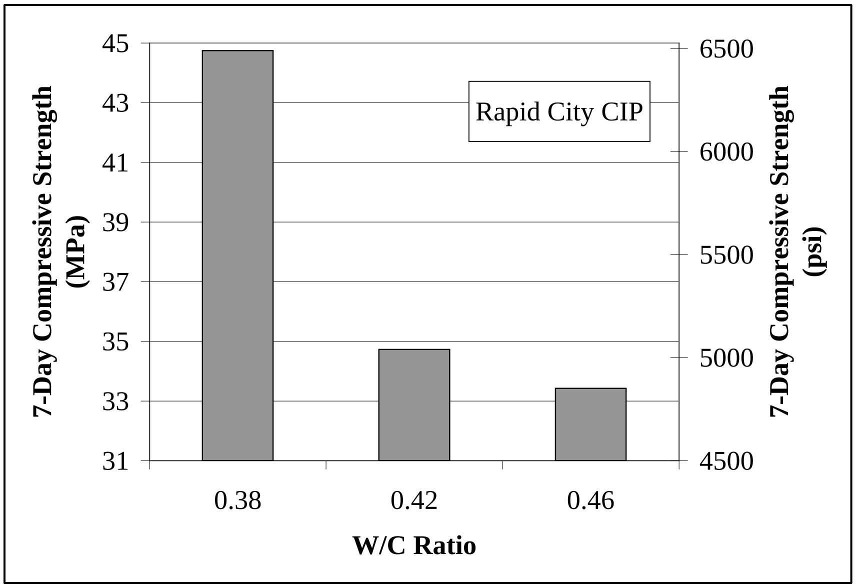


Figure 4.37 7-Day Compressive Strength vs. W/C Ratio for Rapid City Cast-In Place Mix

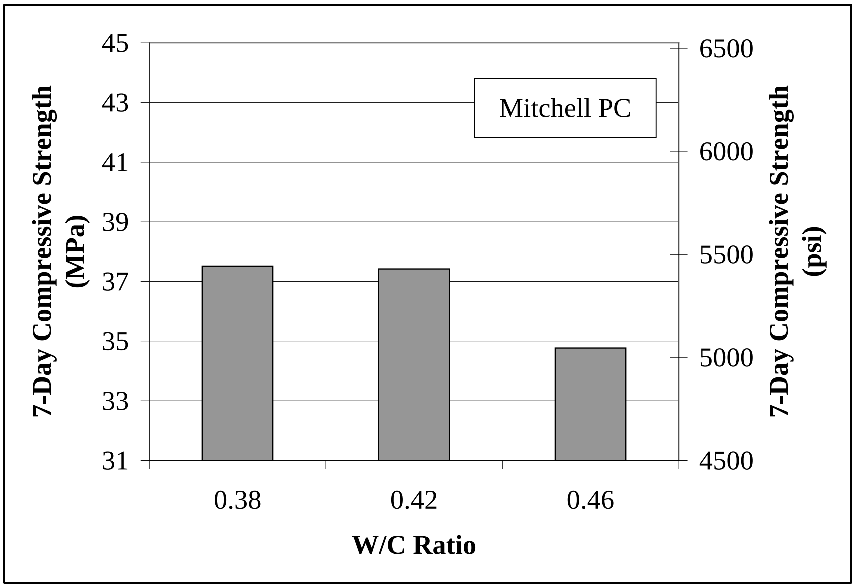


Figure 4.38 7-Day Compressive Strength vs. W/C Ratio for Mitchell Precast Mix

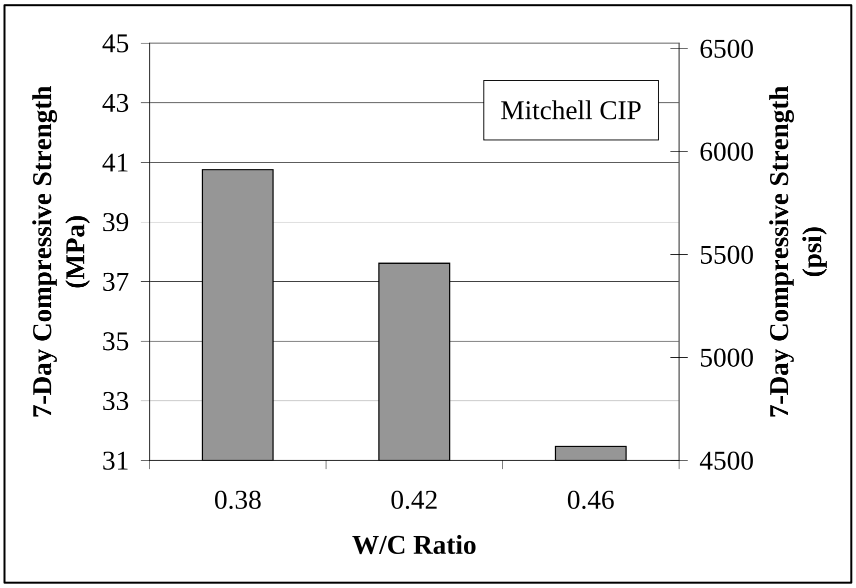


Figure 4.39 7-Day Compressive Strength vs. W/C Ratio for Mitchell Cast-In-Place Mix

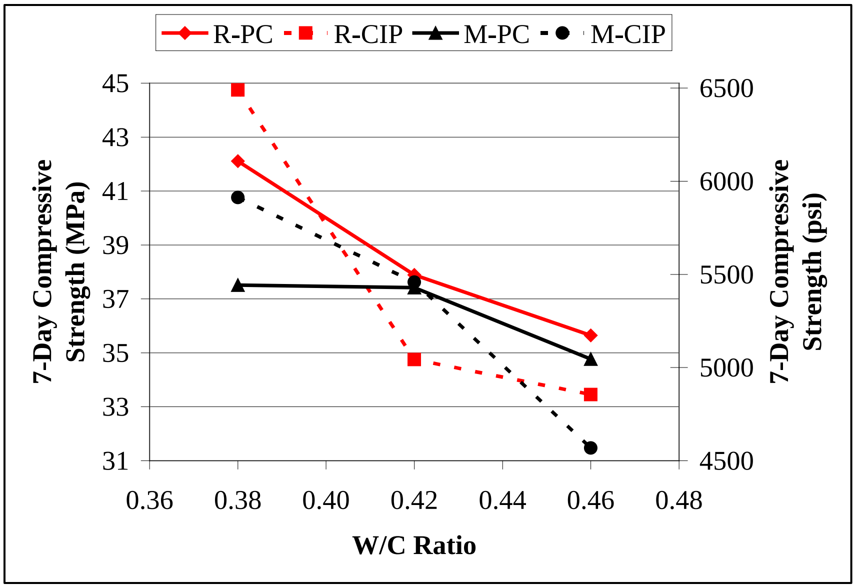


Figure 4.40 7-Day Compressive Strength vs. W/C Ratio for All Mixes

4.5.2 28-Day Compressive Strength

Standard 6″ x 12″ concrete cylinders were tested according to ASTM C 39: "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" (ASTM 2006) after curing for 28 days. Several cylinders from each mix were tested and the average compressive strength values were calculated. The test results are presented in Table 4.10. The average values for 28-day compressive strength are shown in Figures 4.41, 4.42, 4.43, and 4.44, for mixes R-PC, R-CIP, M-PC, and M-CIP, respectively, and summarized in Figure 4.45. The results show that the w/c ratio had a significant effect on all mixes. As the w/c ratio was increased, the 7-day compressive strength of the SCC decreased for all mixes. However, the data is insufficient to develop a relationship between compressive strength and w/c ratio.

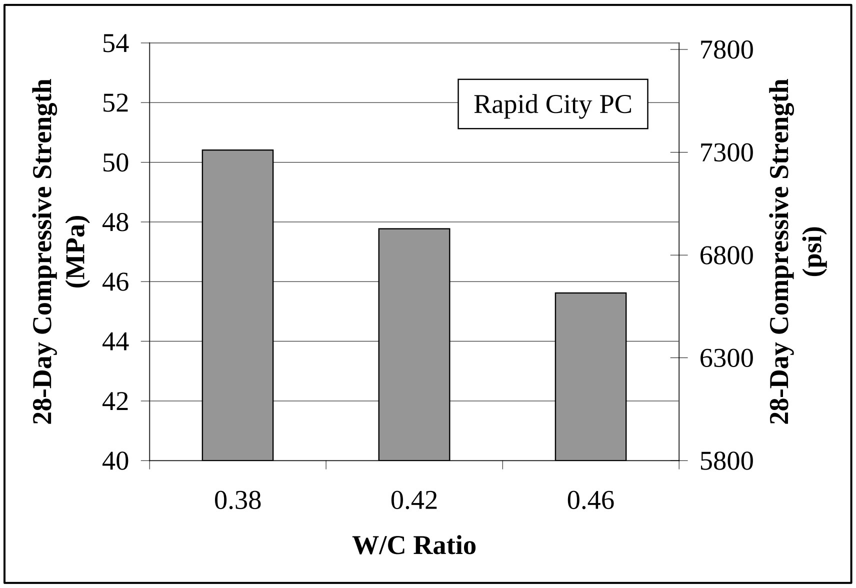


Figure 4.41 28-Day Compressive Strength vs. W/C Ratio for Rapid City Precast Mix

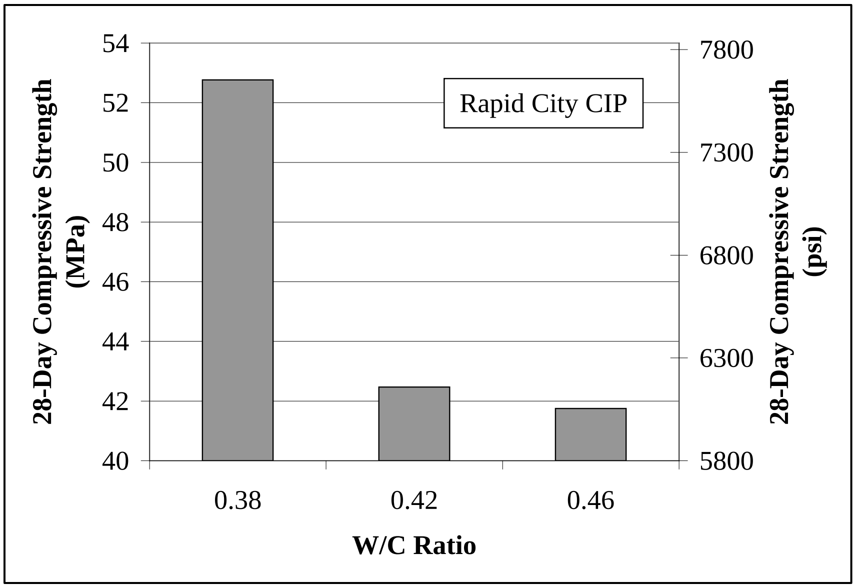


Figure 4.42 28-Day Compressive Strength vs. W/C Ratio for Rapid City Cast-In-Place Mix

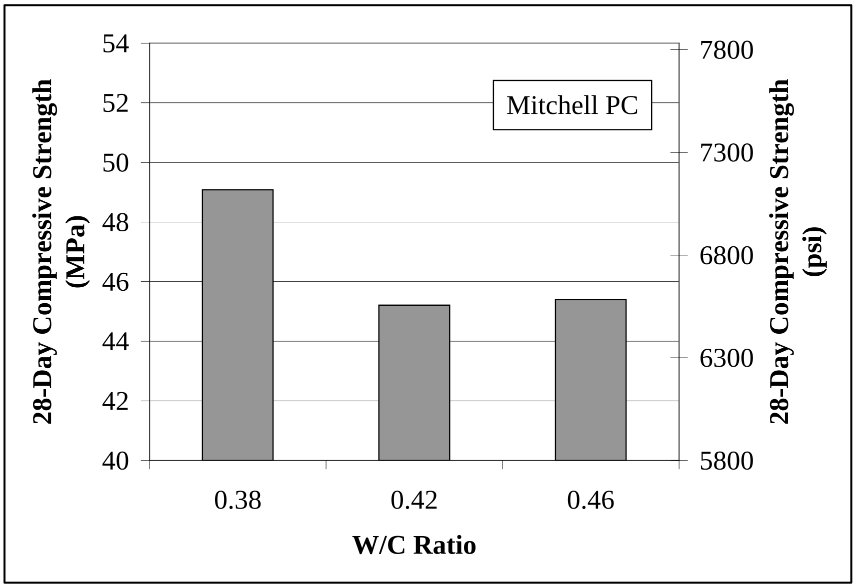


Figure 4.43 28-Day Compressive Strength vs. W/C Ratio for Mitchell Precast Mix

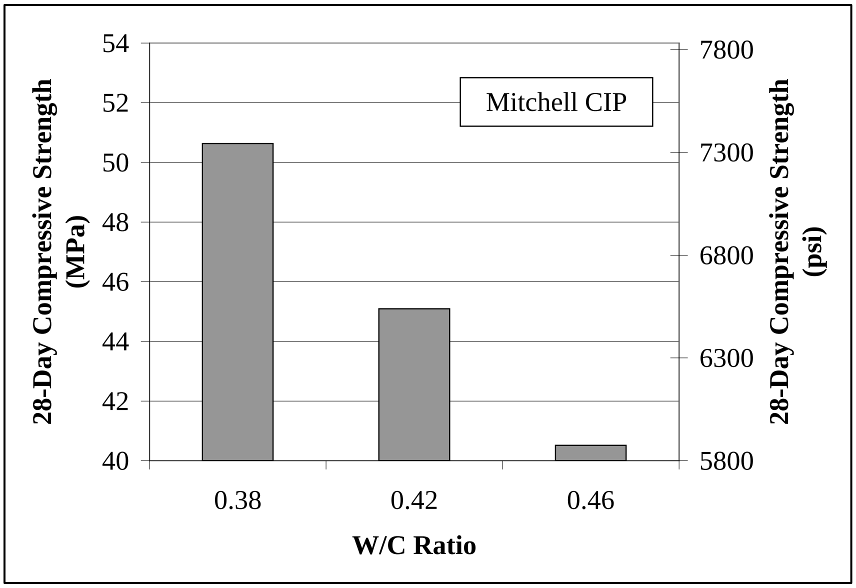


Figure 4.44 28-Day Compressive Strength vs. W/C Ratio for Mitchell Cast-In-Place Mix

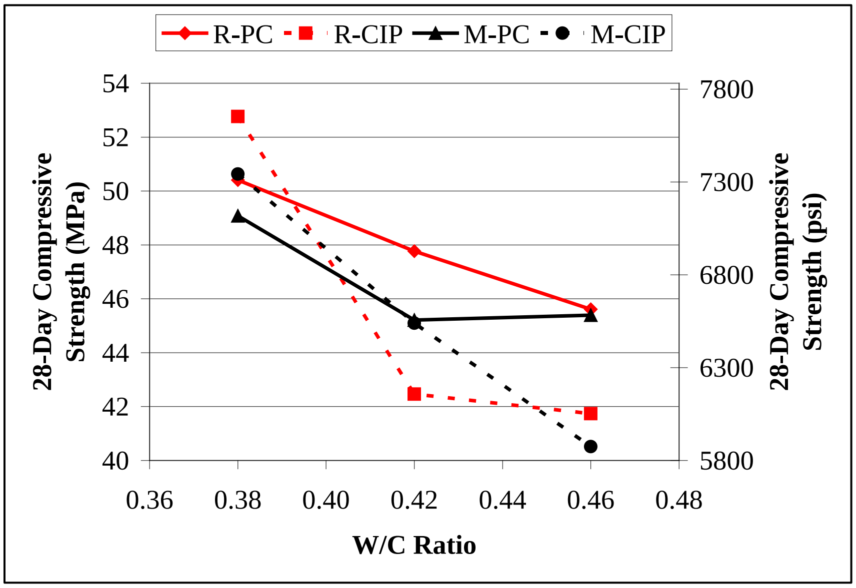


Figure 4.45 28-Day Compressive Strength vs. W/C Ratio for All Mixes

The 7-day compressive strength values were compared to the 28-day compressive strength values. For conventional concrete, the ratio of 28-day compressive strength to 7-day compressive strength has been reported to vary between 1.3 and 1.7, or the ratio of 7-day to 28-day compressive strength is 0.59 to 0.77 (Mindess 2003). The ratio of measured 7-day compressive strength values to measured 28-day compressive strength values in this study is presented in Table 4.11. The values range from 0.76 to 0.85, which indicates comparable strength development of SCC to that of conventional concrete.

Table 4.11 Ratio of 7-Day to 28-Day Measured Compressive Strength

Mix W/C ratio	**0.38**	**0.42**	**0.46**
R-PC	0.84	0.79	0.78
R-CIP	0.85	0.82	0.80
M-PC	0.76	0.83	0.77
M-CIP	0.81	0.83	0.78

4.5.3 28-Day Splitting Tensile Strength

Standard 6″ x 12″ concrete cylinders were tested according to ASTM C 496: "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens" (ASTM 2006) after curing for 28 days. Several cylinders from each mix were tested. The average measured values for 28-day splitting tensile strength are shown in Figures 4.46, 4.47, 4.48, and 4.49 for mixes R-PC, R-CIP, M-PC, and M-CIP, respectively. As the w/c ratio was increased, the 28-day tensile strength of the SCC decreased for all mixes. The splitting tensile strength for all mixes is summarized in Figure 4.50. For conventional concrete, the splitting tensile strength, f_{ct}, ranges between approximately $6\sqrt{f_c'}$ to $7\sqrt{f_c'}$ (Wang 2007). The upper and lower bounds of this range are shown on Figures 4.46 through 4.49. Figure 4.51 shows the measured splitting tensile strength as a function of $\sqrt{f_c'}$. The results indicate that the splitting tensile strength of SCC is comparable to that of conventional concrete.

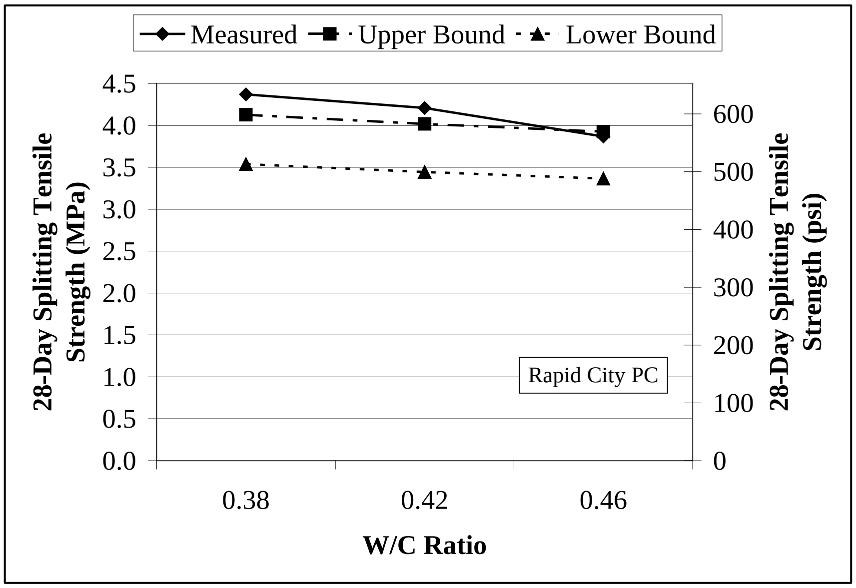


Figure 4.46 Splitting Tensile Strength vs. W/C Ratio for Rapid City Precast Mix

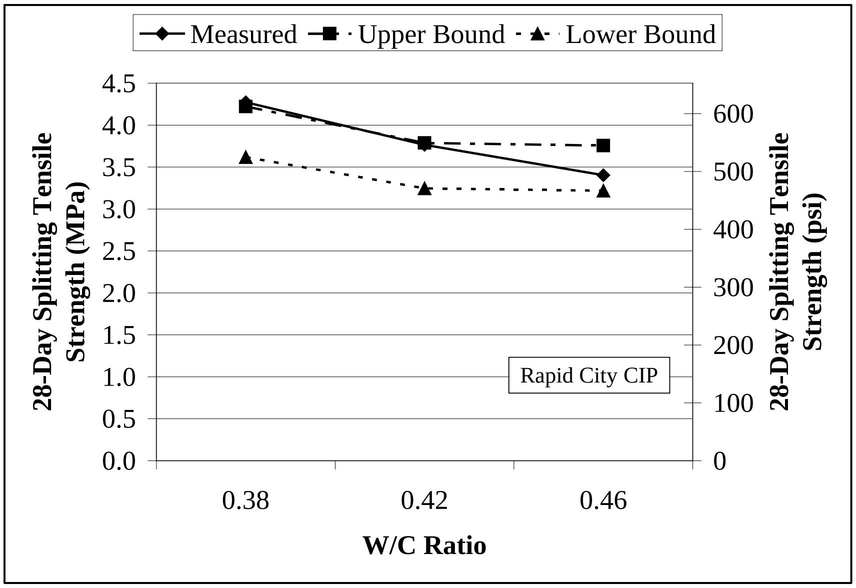


Figure 4.47 Splitting Tensile Strength vs. W/C Ratio for Rapid City Cast-In-Place Mix

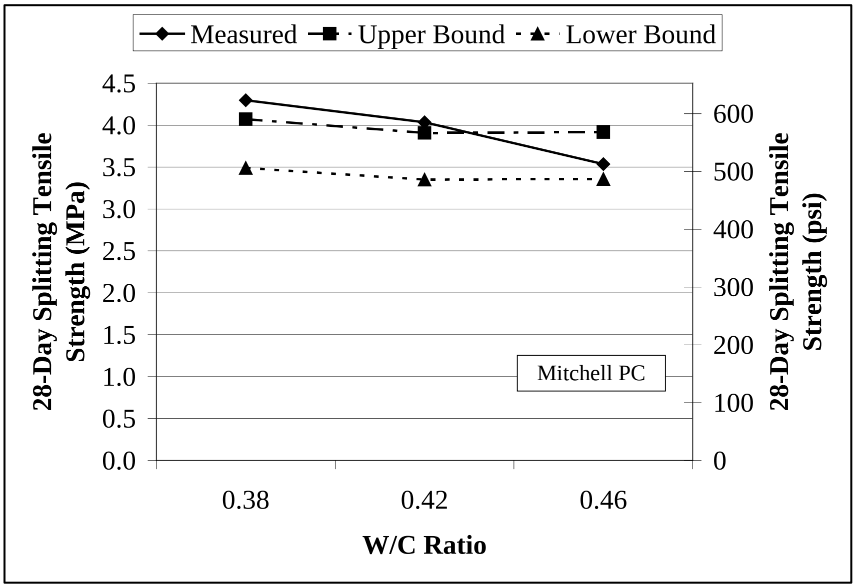


Figure 4.48 Splitting Tensile Strength vs. W/C Ratio for Mitchell Precast Mix

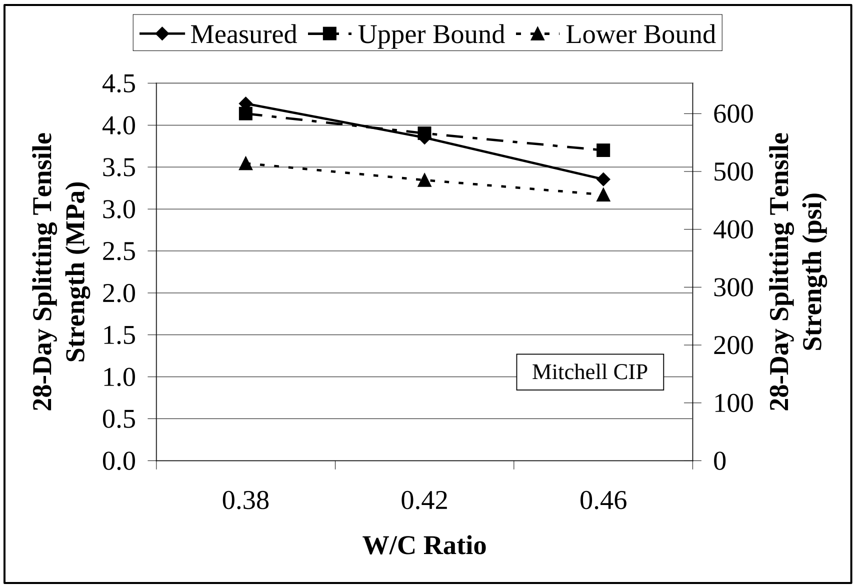


Figure 4.49 Splitting Tensile Strength vs. W/C Ratio for Mitchell Cast-In-Place Mix

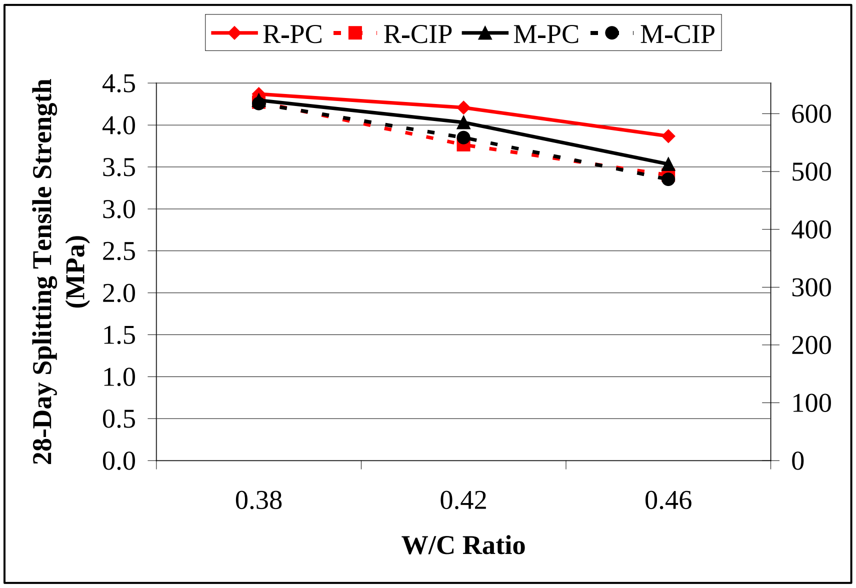


Figure 4.50 Splitting Tensile Strength vs. W/C Ratio for All Mixes

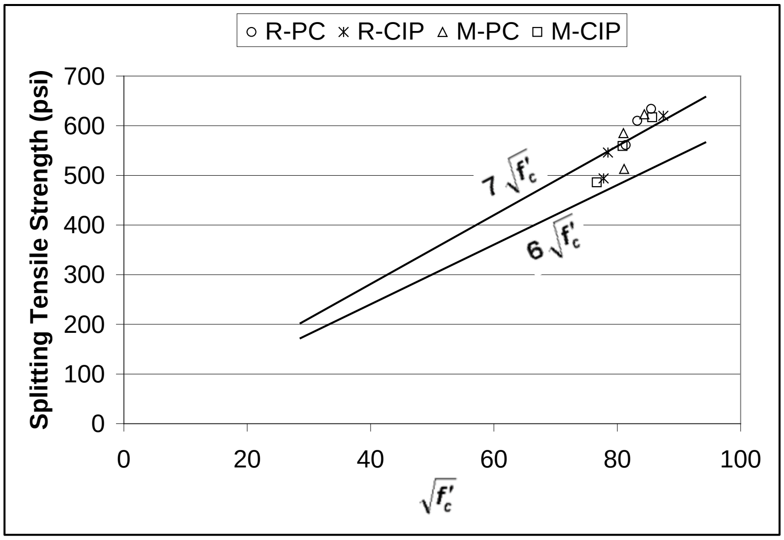


Figure 4.51 Measured 28-Day Splitting Tensile Strength vs $\sqrt{f_c'}$

4.5.4 Modulus of Rupture

Standard 6″ x 6″ x 22″ concrete beams were tested according to ASTM C 78: “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)” (ASTM 2006) to determine the modulus of rupture of the SCC after curing for 28 days. Two beams from each mix were tested to determine the average modulus of rupture for each mix. The average values for modulus of rupture are shown in Figures 4.52, 4.53, 4.54, and 4.55 for mixes R-PC, R-CIP, M-PC, and M-CIP, respectively. The modulus of rupture for all mixes is summarized in Figure 4.56. The American concrete Institute (ACI 2005) provides an empirical equation for the modulus of rupture, f_r, in terms of the concrete compressive strength, f_c', as $f_r = 7.5\sqrt{f_c'}$. The ACI calculated values for the modulus of rupture are shown on Figures.52 through 4.55.

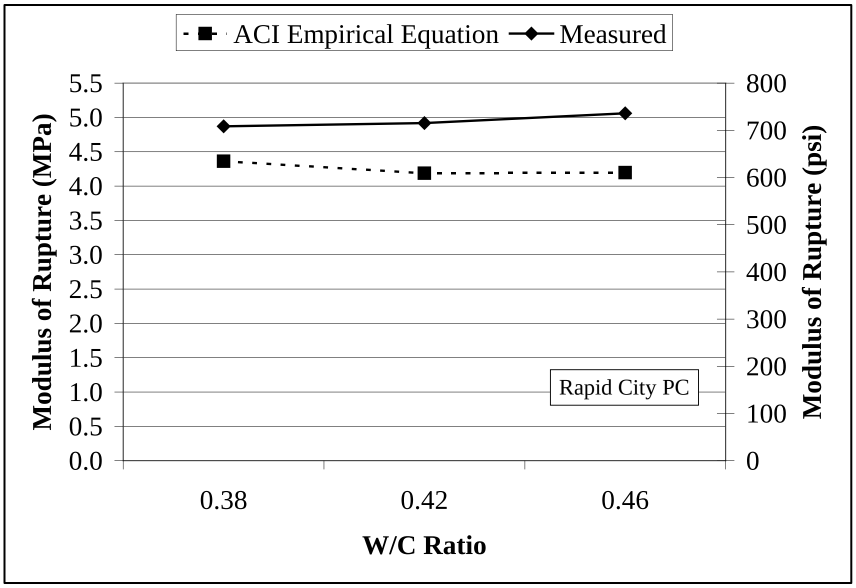


Figure 4.52 Modulus of Rupture vs. W/C Ratio for Rapid City Precast Mix

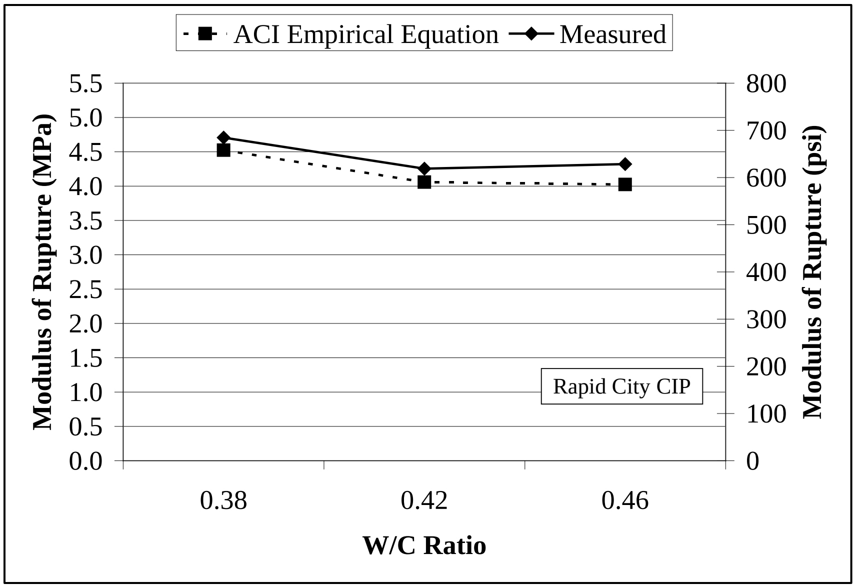


Figure 4.53 Modulus of Rupture vs. W/C Ratio for Rapid City Cast-In-Place Mix

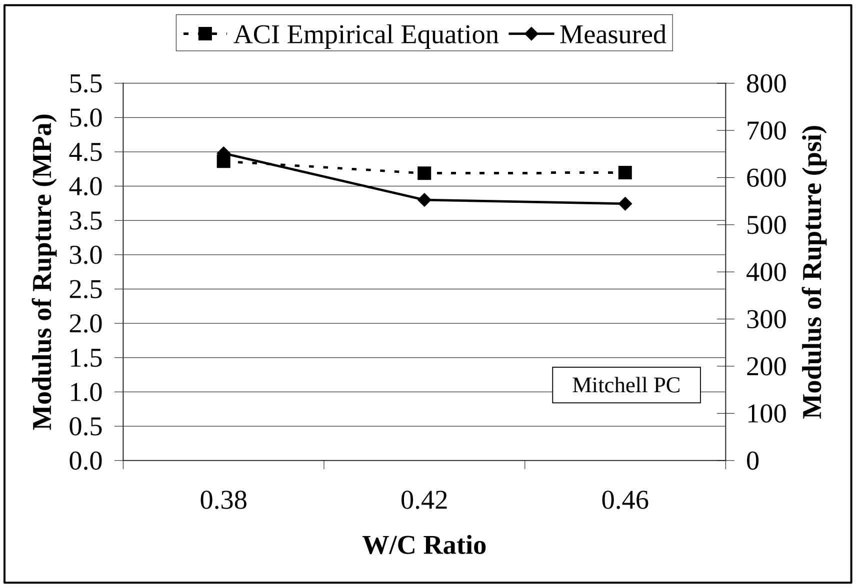


Figure 4.54 Modulus of Rupture vs. W/C Ratio for Mitchell Precast Mix

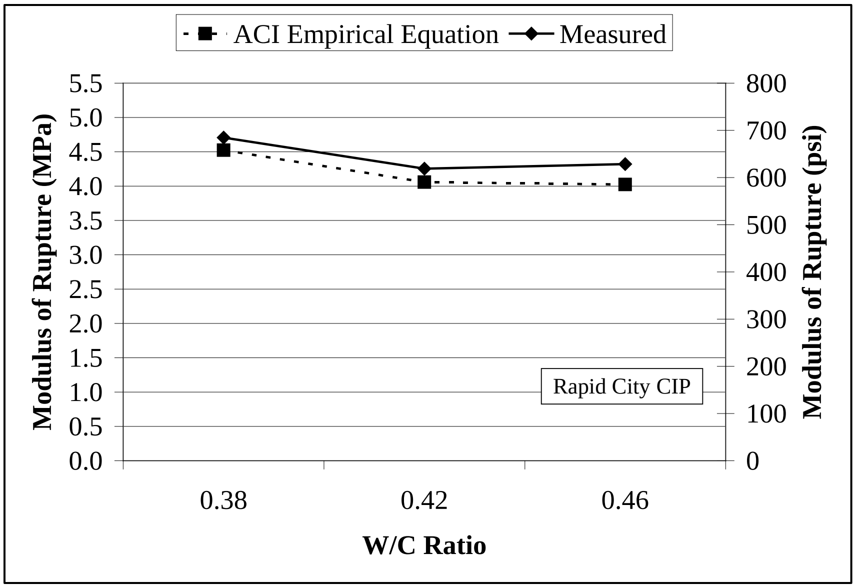


Figure 4.55 Modulus of Rupture vs. W/C Ratio for Mitchell Cast-In-Place Mix

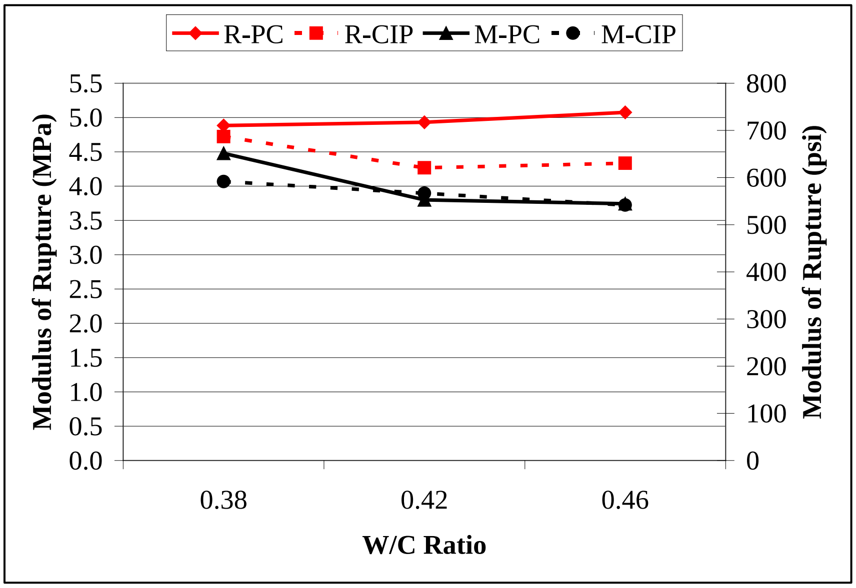


Figure 4.56 Modulus of Rupture vs. W/C Ratio for All Mixes

In general, the modulus of rupture values for R-PC and R-CIP mixes were slightly higher than the values calculated by the ACI equation, while the modulus of rupture values for M-PC and M-CIP mixes were slightly lower than the values calculated by the ACI equation. This may be caused by the variability of the modulus of rupture (Wang et al. 2007), the limited number of beams tested, or the different types of aggregates used. The ratios of the measured modulus of rupture values to those calculated using the ACI equation are shown in Table 4.12. The average measured 28-day flexural strength (modulus of rupture) varied between $6.7\sqrt{f_c'}$ and $9.0\sqrt{f_c'}$ as is shown in Figure 4.57. For conventional concrete, f_r can vary between $7.0\sqrt{f_c'}$ to $13.0\sqrt{f_c'}$ (Wang et al. 2007). It can be inferred from the results that the flexural strength of SCC is comparable to that of conventional concrete and that the ACI empirical equation for determining the modulus of rupture results in reasonably acceptable values when applied to the SCC mixes in this study.

Table 4.12 Ratio of Measured to Calculated Modulus of Rupture

Mix W/C ratio	**0.38**	**0.42**	**0.46**
R-PC	1.10	1.15	1.21
R-CIP	1.04	1.05	1.08
M-PC	1.03	0.91	0.89
M-CIP	0.92	0.93	0.94

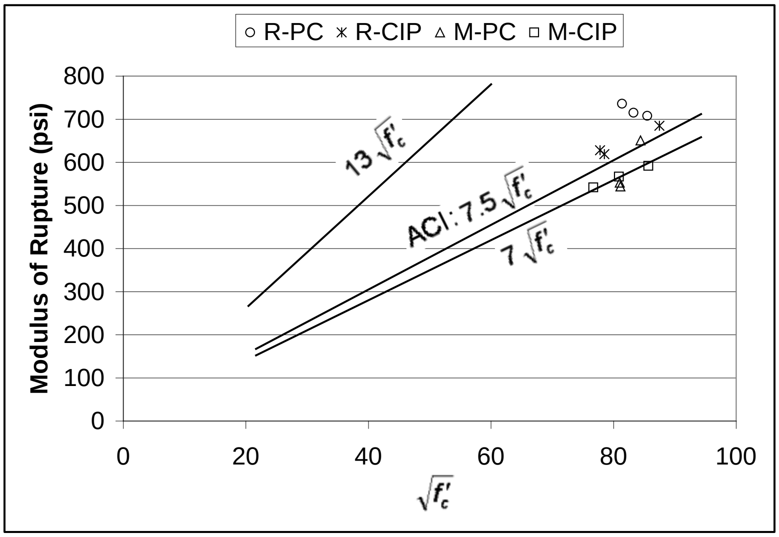


Figure 4.57 Measured 28-Day Flexural Strength vs $\sqrt{f_c'}$

4.5.5 Hardened Visual Stability Index (HVSI)

One hardened concrete cylinder from each batch of each mix design was evaluated according to AASHTO draft specification “Static Segregation of Hardened Self-Consolidating Concrete Cylinders” (AASHTO 2005). The cylinders were sawn in half and assessed for segregation. By visual inspection, all specimens were determined to have a Hardened Visual Stability Index (HVSI) of 0. The HVSI results indicate that there was no apparent segregation and that the concrete was stable for all mixes. Examples of the sawn cylinders are shown in Figure 4.58 (western South Dakota local aggregates) and Figure 4.59 (eastern South Dakota local aggregates).

Figure 4.58 Sawn Concrete Cylinder made with Limestone (Western South Dakota) Aggregates

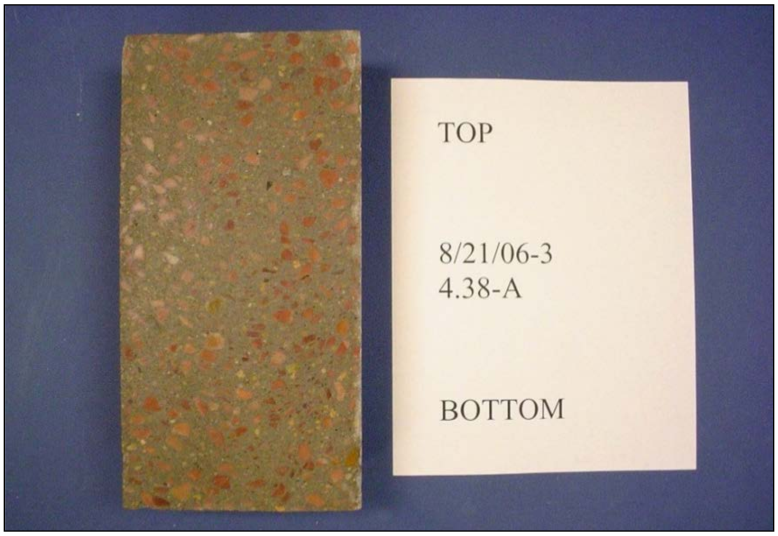


Figure 4.59 Sawn Concrete Cylinder made with Quartzite (Eastern South Dakota) Aggregates

5. CONSTRUCTION AND INSPECTION OF SCC BOX CULVERTS

5.1 Introduction

This chapter covers the on-site construction inspection and inspection after one winter in service of four SCC box culverts. Due to lack of sufficient number of box culverts that had been planned for construction during the course of this study and other scheduling conflicts, only four box culverts (one precast and three cast-in-place culverts) made partially with SCC were constructed and inspected as part of this study. All four culverts were located on Highway 44 in Rapid City, SD, and incorporated limestone coarse aggregate. The precast box culvert was Structure #52-485-337 located at Station 182+24. The cast-in-place box culverts were: Structure #52-462-326 located at Station 43+00, Structure #52-472-331 located at Station 100+35, and Structure #52-489-339 located at Station 201+24.

5.2 Construction Inspection

At least one member of the research team was present during the placement of part or all of the SCC pour for each of the four box culvert structures. Following is an account of the construction inspection.

5.2.1 Structure #52-485-337 (Precast Box Culvert)

Structure #52-485-337 was 136' long and consisted of two-7' x 3' barrel precast box culvert units. The units were 5' and 6' in length. The structure was to be partially built with recycled culvert units taken from the structure that had existed at the same location before the road was widened. The recycled units were made with standard concrete mixture. The road widening on Highway 44 required the addition of new culvert units in order to span the extended road width. The new additional units were made with SCC and were fabricated by Cretex West Concrete Products in Rapid City, SD.

The top slab, bottom slab and walls of the SCC units were 8" thick and were reinforced with two layers of deformed welded wire mesh. The mesh sizes used in the unit were D4.0, D4.5, D5.5, D6.5, and D7.5. A clear cover of 1" was provided throughout. Figure 5.1 shows the reinforcement cage for one of the SCC units.

The first SCC unit was cast on October 25, 2007. The SCC was mixed on location using the batch plant mixer. The mix had an average slump spread of 24.5" and J-Ring spread of 23.5". The measured air content was 5.1% and the measured mix temperature was 75^{o}F. The air temperature during concrete placement was approximately 65^{o}F. The concrete was conveyed from the batch plant mixer to the casting platform by means of a steel hopper that was carried by a forklift. Figure 5.2 shows casting of the SCC unit. The casting operation required only one person to control the discharge of concrete from the hopper. The concrete flowed with ease inside the form and it consolidated without the use of mechanical vibration. Due to the limited capacity of the hopper, the form was filled with concrete in four lifts. The concrete volume needed to cast the unit was approximately 6 cubic yards. The formwork was stripped the day after casting. The finished product showed good consolidation of concrete. The finished concrete surface was free from honeycombing, but there was an insignificant amount of small surface “bugholes” that resulted from entrapment of air bubbles against the formwork. Figure 5.3 shows some completed SCC culvert units.

Figure 5.1 Reinforcement Cage of an SCC Box Culvert Unit

Figure 5.2 Casting of an SCC Box Culvert Unit

Figure 5.3 Completed SCC Box Culvert Units

Standard concrete cylinders were made for the purpose of evaluating concrete segregation using the HVSI method. The cut cylinders exhibited excellent distribution of the course aggregates. Based on the cut cylinders, an HVSI value of “0” was assigned to the SCC mix. Figure 5.4 shows one of the cut cylinders.

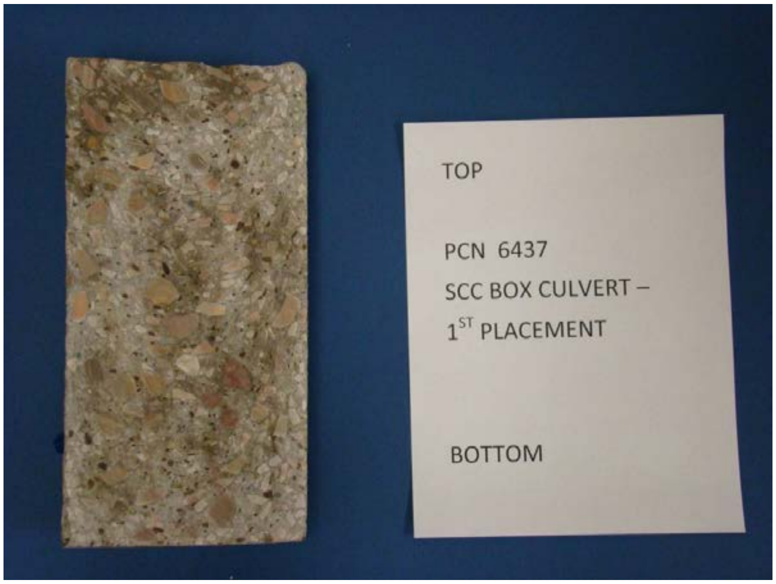


Figure 5.4 HVSI Cylinder from the Precast SCC Units

Structure #52-485-337 was assembled in the summer of 2008 in two stages. In the first stage, the culvert units under the eastbound lanes were installed. In the second stage, the remainder of the structure was completed. The placement of the culvert units under the westbound lanes was observed on September 12, 2008. The construction operation went virtually without any setbacks. The placement of each unit took approximately 15 minutes. Figure 5.5 shows the westbound lanes units under construction.

Figure 5.5 Assembly of the Precast Units of Structure #52-485-337

5.2.2 Structure #52-489-339 (Cast-in-Place Box Culvert)

Structure #52-489-339 was 131' long and consisted of two 10' x 8' barrel cast-in-place box culvert. A 69' long segment of the structure had already been in place under the existing road. The road widening on Highway 44 required the construction of a 63' extension at the south end of the existing culvert in order to span the extended road width. The extension was to be built in two segments with a construction joint at 30' from the end of the existing structure. Only the walls of the new extension were to be cast with SCC. The walls were 7" thick and reinforced with #4 vertical and horizontal steel bars. The specified clear cover was 1". Figure 5.6 shows the extension of Structure #52-489-339 under construction.

Figure 5.6 The Extension of Structure #52-489-339 under Construction

Concrete for the first segment was placed on January 10, 2007. The concrete was mixed at Birdsall batch plant in Rapid City and delivered to the job site in transit mixers. Special pumps mounted on a pickup truck were used to add the superplasticizer and the viscosity modifying admixture to the mixer drum on the job site. Figure 5.7 shows the pickup truck with the pumps. Adding the superplasticizer to the SCC mix on site prevented the superplasticizer from premature evaporation while the concrete was being transported to the site.

Figure 5.7 Superplasticizer and VMA Pump System

The SCC was placed into the formwork by means of a concrete pump. Only one person was needed to hold and guide the flexible hose that was attached to the end of the pump's tremie pipe. Figure 5.8 shows the placement of concrete.

Figure 5.8 Casting of the SCC Mix in Structure #52-489-339

During the concrete placement, the air temperature was approximately 32° F. The slump spread varied between 23.5" and 27.0". The slump spread was always greater than the corresponding J-Ring spread by no more than 2". The measured air content of concrete taken out of the transit mixer varied between 8% and 11%. However, pumping of the concrete resulted in significant air content loss. The air loss due to pumping varied between 3% and 5%. The SCC mix exhibited good flowability inside the formwork. The concrete flowed with ease from the middle to the ends of the wall. However, as the formwork filled up with concrete, the concrete formed a crown of approximately 3" between the middle and the end of the wall. This required the pump hose to be moved along the wall length in order to fill the low spots. The concrete pour was approximately 16 cubic yards and took almost one hour to place.

The formwork was stripped the day after casting. The finished product showed good consolidation of concrete except for one spot in each of the three walls where honeycombing was evident. At each spot, the course aggregates were exposed over approximately 2-3 square feet of surface area. Figure 5.9 shows one of the spots which exhibited honeycombing. The locations of the three affected spots were consistent with the locations where the pump hose was inserted during the placement of concrete. It was later determined that the lack of proper consolidation was the result of not moving the hose outlet above the level of the placed concrete. This problem was corrected in the subsequent SCC pours. The honeycombed areas were later repaired with epoxy mortar.

Figure 5.9 Honeycombing in the Wall of Structure #52-489-339

Concrete for the second wall segment was placed on January 17, 2007, but the research team did not attend the placement of concrete due to short notice.

Standard concrete cylinders were made for the purpose of evaluating concrete segregation using the HVSI method. The cut cylinders exhibited excellent distribution of the course aggregates. Based on the cut cylinders, an HVSI value of “0” was assigned to the SCC mix. Figure 5.10 shows one of the cut cylinders.

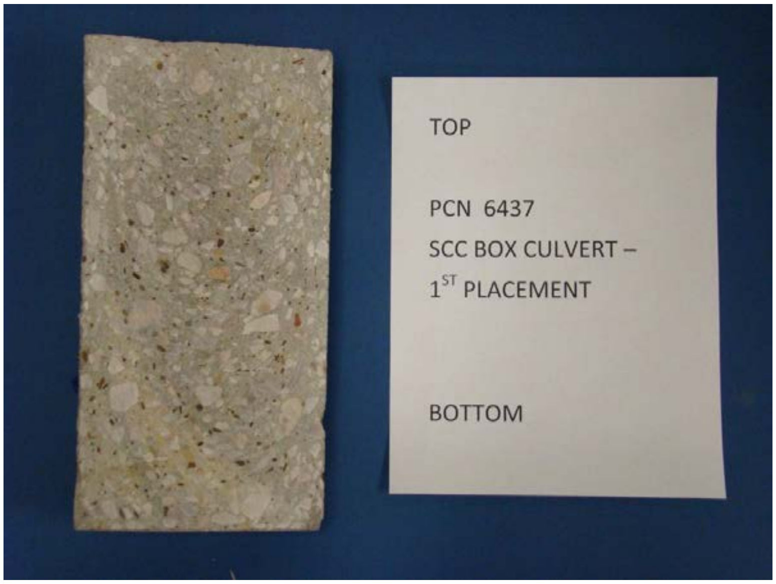
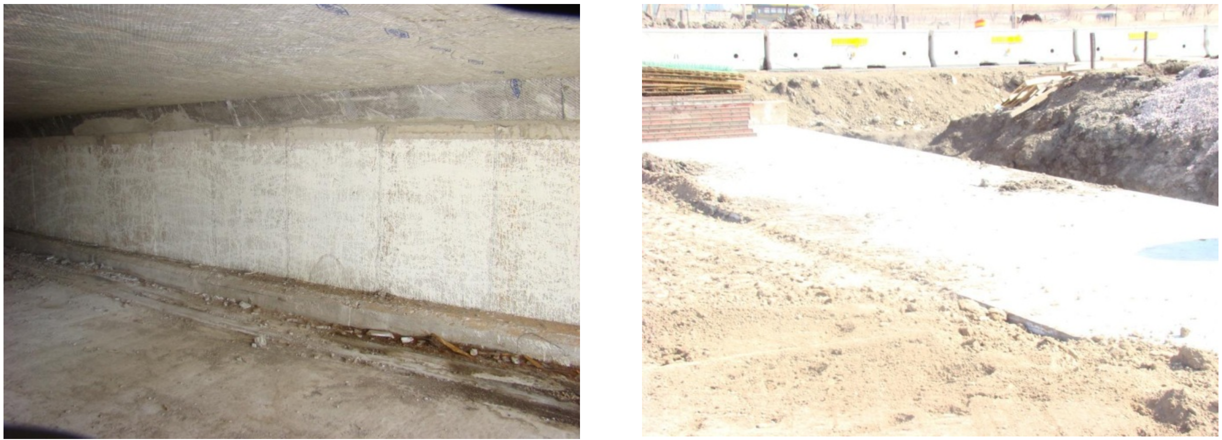


Figure 5.10 HVSI Cylinder from Structure #52-489-339

5.2.3 Structure #52-472-331 (Cast-in-Place Box Culvert)

Structure #52-472-331 was approximately 131' long and consisted of one 12' x 4' barrel cast-in-place box culvert. Only the walls of the box culvert were cast with SCC. The walls were cast on February 21, 2008 and March 17, 2008. Due to the short notice, the research team was unable to attend and observe the placement of the SCC walls. However, representatives from SDDOT were in attendance to ensure compliance with the specifications and to inspect the finished walls after stripping of the formwork. According to SDDOT engineers, the SCC in the walls did not have consolidation problems similar to those exhibited in Structure #52-489-339. The research team inspected the finished structure on April 7, 2008. However, only the interior surface of the walls was visible since exterior excavation had already been backfilled. Figure 5.11 shows pictures of the finished structure.



(a) Finished Wall Interior Surface **(b) Backfill around the Structure**

Figure 5.11 Structure #52-472-331 Following Completion

5.2.4 Structure #52-462-326 (Cast-in-Place Box Culvert)

Structure #52-462-326 was approximately 131' long and consisted of two14' x 4' barrel cast-in-place box culvert. Only the walls of the box culvert were cast with SCC. The walls were cast on three separate occasions: March 10, April 4, and April 7, 2008. Due to the short notice, the research team was unable to attend and observe the placement of the SCC walls on the first two occasions. However, representatives from SDDOT were in attendance to ensure compliance with the specifications and to inspect the finished walls after stripping of the formwork. According to SDDOT engineers, the SCC in the walls did not have consolidation problems similar to those exhibited in Structure #52-489-339. The research team inspected the finished walls while attending the last concrete placement on April 7, 2008. Figure 5.12 shows pictures of the finished walls and the last concrete placement.


(a) Finished Wall Interior Surface **(b) Concrete Placement**

Figure 5.12 Structure #52-462-326 during Construction

5.3 Inspection Following One Winter in Service

Visual inspection of all four box culvert structures was performed on July 10, 2009. The inspection revealed that all four structures were free from surface cracks and any other signs of deterioration. Based on the visual inspection, it can be concluded that the performance of SCC box culverts is similar to conventional concrete box culverts. Pictures of the four box culverts after one winter in service are presented in Figures 5.13 through 5.16.

Figure 5.13 Structure #52-485-337 after One Winter in Service

Figure 5.14 Structure #52-489-339 after One Winter in Service

Figure 5.15 Structure #52-472-331 after One Winter in Service

Figure 5.16 Structure #52-462-326 after One Winter in Service

6. ECONOMIC EVALUATION

As part of a feasibility study in this research, an economic evaluation of SCC was performed. The economic evaluation was based on limited input from the industry. Industry representatives were reluctant to reveal detailed information on the cost of SCC because such information may be utilized by competitors.

Data on the additional cost of producing SCC varied from one source to another. According to one concrete batch plant (Birdsall Sand & Gravel, Rapid City), the cost of producing SCC was approximately 65% higher than that of conventional concrete (Sarver 2008), but no details were provided regarding a breakdown of the cost. On the other hand, a precast concrete plant (Cretex West, Rapid City) estimated the additional cost to be between 20% and 30% (Haeder 2008). The construction contractor did not provide data on the labor cost.

Cost estimate information for 8′ x 8′ single cell box culverts and 8′ x 8′ double cell box culverts was provided by Cretex, Inc. (Anderson 2007). The cost estimate for single cell box culverts is shown in Tables 6.1, 6.2, and 6.3. The cost estimate for double cell box culverts is shown in Tables 6.4, 6.5, and 6.6. The costs are compared for conventional concrete (CC) and self-consolidating concrete (SCC). The cost information presented is for precast box culverts only. The information shows that SCC is estimated to cost approximately 26% more for materials. The labor to produce a conventional concrete box culvert costs approximately four times as much as the labor to produce a SCC box culvert. The total SCC box culvert cost is estimated to be approximately 14% higher than that for conventional concrete. The cost comparison does include the value of improved quality expected from SCC (Anderson 2007).

Table 6.1 8′ x 8′ Single Cell Box Culvert Concrete Material Cost Estimate

	CC	**SCC**
Weight (tons)	10.81	10.81
Cost per ton ($)	28.49	35.84
Total concrete material cost ($)	307.83	387.25
% increase in SCC material cost		25.8

Table 6.2 8′ x 8′ Single Cell Box Culvert Labor Cost Estimate

	CC	**SCC**
Pour truck operator, minutes	20	10
Vibration operator, minutes	20	0
Concrete form filler, minutes	20	10
Finishing time, minutes	15	5
Testing time, minutes	30	10
Total time, minutes	105	35
Total time, hours	1.75	0.58
Labor cost estimate per hour ($)	$25	$25
Total labor cost estimate ($)	$43.75	$14.58
% decrease in SCC labor cost		200

Table 6.3 8′ x 8′ Single Cell Box Culvert Concrete Material and Labor Cost Estimate

	CC	**SCC**
Concrete material + labor cost ($)	351.58	401.83
% increase in SCC box culvert cost		14.3

Table 6.4 8′ x 8′ Double Cell Box Culvert Concrete Material Cost Estimate

	CC	**SCC**
Weight (tons)	19.42	19.42
Cost per ton ($)	28.49	35.84
Total concrete material cost ($)	553.35	696.10
% increase in SCC material cost		25.8

Table 6.5 8′ x 8′ Double Cell Box Culvert Labor Cost Estimate

	CC	**SCC**
Pour truck operator, minutes	45	25
Vibration operator, minutes	45	0
Concrete form filler, minutes	45	25
Finishing time, minutes	30	10
Testing time, minutes	30	10
Total time, minutes	195	70
Total time, hours	3.25	1.17
Labor cost estimate per hour ($)	25	25
Total labor cost estimate ($)	81.25	29.17
% decrease in SCC labor cost		179

Table 6.6 8′ x 8′ Double Cell Box Culvert Concrete Material and Labor Cost Estimate

	CC	**SCC**
Concrete material + labor cost ($)	634.60	725.27
% increase in SCC box culvert cost		14.3

7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

The work presented in this interim report is part of SDDOT Research Project SD2005-13, “Structural Applications of Self-Consolidating Concrete.” The objectives of this research were to evaluate the feasibility and performance of self-consolidating concrete (SCC) made with local aggregates for use in cast-in-place and precast concrete applications and to develop draft specifications, acceptance criteria, mix qualifications, and guidelines for use of SCC by SDDOT. Box culverts were designated as the first type of structures to potentially be constructed by SDDOT using SCC.

An experimental research study was conducted at South Dakota State University to determine the feasibility of constructing box culverts in South Dakota using SCC made with local aggregates. The research included a literature search and review, development of SCC mix designs utilizing South Dakota local aggregates, aggregate testing, materials testing of both fresh and hardened SCC properties, and development of SCC special provisions in coordination with SDDOT staff and industry representatives.

Twelve SCC mixes were studied. The parameters were aggregate type, w/c ratio, and mixing duration. The mixes were developed for two types of coarse aggregates: two-stage crushed quartzite (eastern South Dakota) and crushed limestone (western South Dakota). Two mixing durations were utilized to simulate precast and cast-in-place applications. In all, four application types were considered in this study to represent precast and cast-in-place applications using either western South Dakota or eastern South Dakota aggregates. For each application type, three w/c ratios, 0.38, 0.42, and 0.46, were investigated. The w/c ratio was varied by simultaneous adjustment of the water and the cement quantities to maintain the same mix yield volume under different w/c ratios. The ratio of the high range water reducing admixture (HRWRA) to the cement was maintained the same within the same mix type. Therefore, the amount of HRWRA was decreased as the w/c ratio was increased.

Fresh concrete tests were performed on the SCC to evaluate flowability, passing ability, and segregation resistance. Hardened concrete tests were performed to measure compressive strength, tensile strength, modulus of rupture, and segregation.

In addition to the laboratory work, the project included on-site construction observation and field inspection under service conditions of conventional concrete box culverts and SCC box culverts in order to determine potential economic benefits of SCC and the finished quality of the structures.

The tests performed to evaluate the properties of the aggregates used were:

- ASTM C29: “Standard Test Method for Bulk Density (“Unit Weight”) and Voids in Aggregate,” ASTM C136: “Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates,”
- ASTM C127: “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate,”
- ASTM C128: “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate,” and
- ASTM C117: “Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve by Washing.”

The tests performed to evaluate the fresh concrete properties were:

- ASTM C 231: “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method,”
- ASTM C 1611: “Standard Test Method for Slump Flow of Self-Consolidating Concrete,”
- ASTM C 1621: “Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring,”

- ASTM C 1064: “Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete,”
- The L-box test according to the Interim Guidelines for the Use of Self-Consolidating Concrete in Precast/Prestressed Concrete Institute Member Plants, and
- The Column Segregation test, later approved as ASTM C 1610: “Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique.”

The tests performed to evaluate the hardened properties of the SCC were:

- ASTM C 39: “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,”
- ASTM C 78: “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading),”
- ASTM C 496: “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens,” and
- AASHTO draft “Standard Method of Test for Static Segregation of Hardened Self-Consolidating Concrete Cylinders.”

7.2 Conclusions

The base mix designs were all founded on a w/c ratio of 0.42. The base mix designs are shown in Table 4.5. To create different mix designs, the w/c ratio was varied as the paste volume was kept constant. As the amount of water in the mix increased, the amount of cement in the mix decreased. The mix designs had the same yield because the paste volume was kept constant. The amount of admixtures in the mixes was based on the amount of cement in the mix. Therefore, the amount of the HRWR admixture in the mixes varied with the amount of cement. The mix designs with varying w/c ratios are shown in Tables 4.6, 4.7, and 4.8.

Fresh concrete tests were performed on the SCC to evaluate flowability, passing ability, and segregation resistance. Hardened concrete tests were performed to measure compressive strength, tensile strength, modulus of rupture, and segregation. The following conclusions were made following this research. Based on the experimental results, the following conclusions were made.

Plastic SCC Behavior

1. As the w/c ratio increased, the SCC flowability (slump) typically increased.
2. As the w/c ratio increased, the blocking potential typically decreased.
3. As the w/c ratio increased, the T_{20} value decreased.
4. As the w/c ratio increased, the L-Box H2/H1 ratio typically increased.
5. As the w/c ratio increased, the air content of the precast mixes (short-duration mixing) decreased while the air content of the cast-in-place mixes remained practically unchanged.

Hardened SCC Behavior

6. As w/c ratio increased, the SCC compressive strength decreased.
7. The 7-day compressive strength values were compared to the 28-day compressive strength values. The results indicated that the strength development rate of SCC is comparable to that of conventional concrete.
8. As the w/c ratio increased, the splitting tensile strength decreased. The results also indicated that the relationship between splitting tensile strength and the compressive strength of SCC is comparable to that of conventional concrete.
9. As the w/c ratio increased, the modulus of rupture of the SCC decreased. The results indicated that the relationship between modulus of rupture and the compressive strength of SCC is comparable to that of

conventional concrete and that the ACI empirical equation for determining the modulus of rupture is suitable for use with SCC.

Constructability of SCC Box Culverts

10. The major precasting plants and concrete batch plants in South Dakota are well equipped to successfully produce SCC for precast and cast-in-place highway structures.
11. According to industry representatives, the production cost of SCC was 20% to 65% higher than that of conventional concrete.
12. Casting SCC was significantly faster than casting conventional concrete and required approximately one-quarter to one-third of the labor force needed to cast a similar amount of conventional concrete.
13. The SCC box culverts did not show any signs of early deterioration following one winter in service.

General

14. When properly sized and shaped, South Dakota local aggregates were found to be suitable for producing SCC.
15. All SCC mix designs considered in this study were found stable, under the laboratory conditions, by visual stability index and hardened visual stability index.
16. The highest w/c ratio used (0.46) resulted in the most economical SCC mix (least amounts of cement and HRWRA) and the highest fluidity.
17. The measured SCC 28-day compressive strength varied between 40.5 MPa (5880 psi) and 52.8 MPa (7650 psi). Even at a w/c ratio of 0.46, the concrete strength was adequate for most cast-in-place and precast applications.
18. The measured air content was either within or higher than the limits set by SDDOT for conventional concrete. The air content can be easily modified by adjusting the amount of the air entraining admixture. Allowance for air loss due to pumping should be considered.
19. Except for one of the twelve mixes considered in this study, the measured slump spread values were 500 mm (20 in) or more.

7.3 Recommendations

Based on the results of this study, the following recommendations are made:

1. The South Dakota Department of Transportation should permit the use of SCC for cast-in-place and precast applications.
2. It is recommended that SDDOT adopt the special provisions that were developed in this study for the use of SCC for the construction of cast-in-place and pre-cast box culverts. The development of the special provisions was a collaborative effort among the researchers at SDSU, SDDOT, and members of the concrete industry. The special provisions are presented in Appendix C.
3. The concrete producer should be responsible for the design of a SCC mix to meet the client’s stated performance levels. The special provisions that were developed in this study set performance levels and acceptance criteria for SCC mixtures when used for the fabrication of cast-in-place and precast box culverts in South Dakota.
4. The SDDOT concrete technicians should be trained to conduct the slump spread (ASTM C 1611) and the J-Ring spread (ASTM C 1621) SCC acceptance tests.
5. The performance of the slump spread and the J-Ring spread tests requires a non-absorbent board and a steel J-Ring apparatus. SDDOT should purchase and maintain an adequate number of non-absorbent boards and J-Ring apparatus. The purchase cost of such tools is nominal.

6. For cast-in-place SCC applications where the concrete is expected to remain in the concrete mixer for an extended duration before it is discharged, the HRWRA should be added and mixed on the jobsite immediately before concrete discharge. This will reduce the potential for evaporation of the HRWRA and will ensure adequate slump spread.
7. The slump spread lower limit in the proposed special provisions has been set at 560 mm (22 in.). For applications such as single footings or columns that do not require the concrete to flow for a long distance in the formwork, a 500 mm (20 in) spread appears to be adequate. For such applications, it is recommended that the slump spread lower limit be reduced to 500 mm (20 in). This would allow for greater flexibility and more efficient use of application-based performance measures.

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APPENDIX A: BATCH WEIGHTS

Table A.1 Batch Weights for Rapid City Precast Mix

Mix date	7/12/2006
Mix ID	7/12/06-1
Mix description	R-PC Mix 1.42-D

Batch size, cu yd	0.1

Mix design

Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	738
W/C ratio	0.42
Water lb/cu yd	309.96
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00

Correction for excess water on aggregates

Coarse aggr. moisture, %	1.017
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0066
Coarse aggr. corr., lb/cu yd	8.59
Fine aggr. moisture, %	3.38
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0222
Fine aggr. corr., lb	33.16
Excess water correction, lb/cu yd	41.76

Batch

Coarse, lb	130.16
Fine, lb	152.82
Cement, lb	73.80
Water, lb	26.82
Daravair M, mL	24.0
Daratard 17, mL	65.5
ADVA 555, mL	371.0

Table A.1 Batch Weights for Rapid City Precast Mix (continued)

Mix date	7/13/2006
Mix ID	7/13/06-1
Mix description	R-PC Mix 1.42-E
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	738
W/C ratio	0.42
Water lb/cu yd	309.96
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.017
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0066
Coarse aggr. corr., lb/cu yd	8.59
Fine aggr. moisture, %	3.38
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0222
Fine aggr. corr., lb	33.16
Excess water correction, lb/cu yd	41.76
Batch	
Coarse, lb	130.16
Fine, lb	152.82
Cement, lb	73.80
Water, lb	26.82
Daravair M, mL	24.0
Daratard 17, mL	65.5
ADVA 555, mL	371.0

Table A.1 Batch Weights for Rapid City Precast Mix (continued)

Mix date	7/13/2006
Mix ID	7/13/06-2
Mix description	R-PC Mix 1.38-A
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	780.38
W/C ratio	0.38
Water lb/cu yd	296.54
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.111
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0076
Coarse aggr. corr., lb/cu yd	9.80
Fine aggr. moisture, %	3.45
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0229
Fine aggr. corr., lb	34.18
Excess water correction, lb/cu yd	43.99
Batch	
Coarse, lb	130.28
Fine, lb	152.92
Cement, lb	78.04
Water, lb	25.26
Daravair M, mL	25.4
Daratard 17, mL	69.2
ADVA 555, mL	392.3

Table A.1 Batch Weights for Rapid City Precast Mix (continued)

Mix date	7/14/2006
Mix ID	7/14/06-1
Mix description	R-PC Mix 1.38-B
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	780.38
W/C ratio	0.38
Water lb/cu yd	296.54
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.111
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0076
Coarse aggr. corr., lb/cu yd	9.80
Fine aggr. moisture, %	3.45
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0229
Fine aggr. corr., lb	34.18
Excess water correction, lb/cu yd	43.99
Batch	
Coarse, lb	130.28
Fine, lb	152.92
Cement, lb	78.04
Water, lb	25.26
Daravair M, mL	25.4
Daratard 17, mL	69.2
ADVA 555, mL	392.3

Table A.1 Batch Weights for Rapid City Precast Mix (continued)

Mix date	7/17/2006
Mix ID	7/17/06-1
Mix description	R-PC Mix 1.46-A
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	700.08
W/C ratio	0.46
Water lb/cu yd	322.04
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.089
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0074
Coarse aggr. corr., lb/cu yd	9.53
Fine aggr. moisture, %	4.37
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0319
Fine aggr. corr., lb	47.69
Excess water correction, lb/cu yd	57.21
Batch	
Coarse, lb	130.25
Fine, lb	154.27
Cement, lb	70.01
Water, lb	26.48
Daravair M, mL	22.8
Daratard 17, mL	62.1
ADVA 555, mL	352.0

Table A.1 Batch Weights for Rapid City Precast Mix (continued)

Mix date	7/17/2006
Mix ID	7/17/06-2
Mix description	R-PC Mix 1.46-B
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	700.08
W/C ratio	0.46
Water lb/cu yd	322.04
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.089
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0074
Coarse aggr. corr., lb/cu yd	9.53
Fine aggr. moisture, %	4.37
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0319
Fine aggr. corr., lb	47.69
Excess water correction, lb/cu yd	57.21
Batch	
Coarse, lb	130.25
Fine, lb	154.27
Cement, lb	70.01
Water, lb	26.48
Daravair M, mL	22.8
Daratard 17, mL	62.1
ADVA 555, mL	352.0

Table A.2 Batch Weights for Rapid City Cast-In-Place Mix

Mix date	7/19/2006
Mix ID	7/19/06-2
Mix description	R-CIP Mix 2.42-A
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	738
W/C ratio	0.42
Water lb/cu yd	309.96
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00
Correction for excess water on aggregates	
Coarse aggr. moisture, %	0.904
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0055
Coarse aggr. corr., lb/cu yd	7.14
Fine aggr. moisture, %	3.99
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0281
Fine aggr. corr., lb	42.06
Excess water correction, lb/cu yd	49.20
Batch	
Coarse, lb	130.01
Fine, lb	153.71
Cement, lb	73.80
Water, lb	26.08
Daravair M, mL	24.0
Daratard 17, mL	65.5
ADVA 555, mL	371.0

Table A.2 Batch Weights for Rapid City Cast-In-Place Mix (continued)

Mix date	7/24/2006
Mix ID	7/24/06-1
Mix description	R-CIP Mix 2.42-B
Batch size, cu yd	0.1

Mix design

Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	738
W/C ratio	0.42
Water lb/cu yd	309.96
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00

Correction for excess water on aggregates

Coarse aggr. moisture, %	1.135
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0078
Coarse aggr. corr., lb/cu yd	10.11
Fine aggr. moisture, %	7.46
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0625
Fine aggr. corr., lb	93.48
Excess water correction, lb/cu yd	103.59

Batch

Coarse, lb	130.31
Fine, lb	158.85
Cement, lb	73.80
Water, lb	20.64
Daravair M, mL	24.0
Daratard 17, mL	65.5
ADVA 555, mL	371.0

Table A.2 Batch Weights for Rapid City Cast-In-Place Mix (continued)

Mix date	7/25/2006
Mix ID	7/25/06-1
Mix description	R-CIP Mix 2.38-B
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	780.38
W/C ratio	0.38
Water lb/cu yd	296.54
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.527
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0117
Coarse aggr. corr., lb/cu yd	15.17
Fine aggr. moisture, %	5.71
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0452
Fine aggr. corr., lb	67.58
Excess water correction, lb/cu yd	82.75
Batch	
Coarse, lb	130.82
Fine, lb	156.26
Cement, lb	78.04
Water, lb	21.38
Daravair M, mL	25.4
Daratard 17, mL	69.2
ADVA 555, mL	392.3

Table A.2 Batch Weights for Rapid City Cast-In-Place Mix (continued)

Mix date	7/26/2006
Mix ID	7/26/06-1
Mix description	R-CIP Mix 2.38-C
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	780.38
W/C ratio	0.38
Water lb/cu yd	296.54
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.285
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0093
Coarse aggr. corr., lb/cu yd	12.04
Fine aggr. moisture, %	6.97
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0577
Fine aggr. corr., lb	86.20
Excess water correction, lb/cu yd	98.24
Batch	
Coarse, lb	130.50
Fine, lb	158.12
Cement, lb	78.04
Water, lb	19.83
Daravair M, mL	25.4
Daratard 17, mL	69.2
ADVA 555, mL	392.3

Table A.2 Batch Weights for Rapid City Cast-In-Place Mix (continued)

Mix date	7/18/2006
Mix ID	7/18/06-1
Mix description	R-CIP Mix 2.46-A
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	700.08
W/C ratio	0.46
Water lb/cu yd	322.04
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00

Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.089
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0074
Coarse aggr. corr., lb/cu yd	9.53
Fine aggr. moisture, %	4.37
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0319
Fine aggr. corr., lb	47.69
Excess water correction, lb/cu yd	57.21

Batch	
Coarse, lb	130.25
Fine, lb	154.27
Cement, lb	70.01
Water, lb	26.48
Daravair M, mL	22.8
Daratard 17, mL	62.1
ADVA 555, mL	352.0

Table A.2 Batch Weights for Rapid City Cast-In-Place Mix (continued)

Mix date	7/19/2006
Mix ID	7/19/06-1
Mix description	R-CIP Mix 2.46-B
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	700.08
W/C ratio	0.46
Water lb/cu yd	322.04
Daravair M, oz/cwt	1.10
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	17.00
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.089
Coarse aggr. absorption, %	0.350
Coarse aggr. correction coeff.	0.0074
Coarse aggr. corr., lb/cu yd	9.53
Fine aggr. moisture, %	4.37
Fine aggr. absorption, %	1.14
Fine aggr. correction coeff.	0.0319
Fine aggr. corr., lb	47.69
Excess water correction, lb/cu yd	57.21
Batch	
Coarse, lb	130.25
Fine, lb	154.27
Cement, lb	70.01
Water, lb	26.48
Daravair M, mL	22.8
Daratard 17, mL	62.1
ADVA 555, mL	352.0

Table A.3 Batch Weights for Mitchell Precast Mix

Mix date	8/21/2006
Mix ID	8/21/06-2
Mix description	M-PC Mix 4.42-B
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	738
W/C ratio	0.42
Water lb/cu yd	309.96
Daravair M, oz/cwt	0.94
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	12.39
Correction for excess water on aggregates	
Coarse aggr. moisture, %	0.897
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0056
Coarse aggr. corr., lb/cu yd	7.21
Fine aggr. moisture, %	0.34
Fine aggr. absorption, %	0.30
Fine aggr. correction coeff.	0.0004
Fine aggr. corr., lb	0.62
Excess water correction, lb/cu yd	7.84
Batch	
Coarse, lb	130.02
Fine, lb	149.56
Cement, lb	73.80
Water, lb	30.21
Daravair M, mL	20.5
Daratard 17, mL	65.5
ADVA 555, mL	270.5

Table A.3 Batch Weights for Mitchell Precast Mix (continued)

Mix date	8/23/2006
Mix ID	8/23/06-1
Mix description	M-PC Mix 4.42-C
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	738
W/C ratio	0.42
Water lb/cu yd	309.96
Daravair M, oz/cwt	0.94
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	12.39
Correction for excess water on aggregates	
Coarse aggr. moisture, %	0.981
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0064
Coarse aggr. corr., lb/cu yd	8.30
Fine aggr. moisture, %	0.74
Fine aggr. absorption, %	0.30
Fine aggr. correction coeff.	0.0044
Fine aggr. corr., lb	6.57
Excess water correction, lb/cu yd	14.87
Batch	
Coarse, lb	130.13
Fine, lb	150.16
Cement, lb	73.80
Water, lb	29.51
Daravair M, mL	20.5
Daratard 17, mL	65.5
ADVA 555, mL	270.5

Table A.3 Batch Weights for Mitchell Precast Mix (continued)

Mix date	8/21/2006
Mix ID	8/21/06-3
Mix description	M-PC Mix 4.38-A
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	780.38
W/C ratio	0.38
Water lb/cu yd	296.54
Daravair M, oz/cwt	0.94
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	12.39
Correction for excess water on aggregates	
Coarse aggr. moisture, %	0.897
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0056
Coarse aggr. corr., lb/cu yd	7.21
Fine aggr. moisture, %	0.34
Fine aggr. absorption, %	0.30
Fine aggr. correction coeff.	0.0004
Fine aggr. corr., lb	0.62
Excess water correction, lb/cu yd	7.84
Batch	
Coarse, lb	130.02
Fine, lb	149.56
Cement, lb	78.04
Water, lb	28.87
Daravair M, mL	21.7
Daratard 17, mL	69.2
ADVA 555, mL	286.0

Table A.3 Batch Weights for Mitchell Precast Mix (continued)

Mix date	8/22/2006
Mix ID	8/22/06-1
Mix description	M-PC Mix 4.38-B

Batch size, cu yd	0.1

Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	780.38
W/C ratio	0.38
Water lb/cu yd	296.54
Daravair M, oz/cwt	0.94
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	12.39

Correction for excess water on aggregates	
Coarse aggr. moisture, %	0.640
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0030
Coarse aggr. corr., lb/cu yd	3.90
Fine aggr. moisture, %	0.48
Fine aggr. absorption, %	0.30
Fine aggr. correction coeff.	0.0018
Fine aggr. corr., lb	2.65
Excess water correction, lb/cu yd	6.55

Batch	
Coarse, lb	129.69
Fine, lb	149.77
Cement, lb	78.04
Water, lb	29.00
Daravair M, mL	21.7
Daratard 17, mL	69.2
ADVA 555, mL	286.0

Table A.3 Batch Weights for Mitchell Precast Mix (continued)

Mix date	8/22/2006
Mix ID	8/22/06-2
Mix description	M-PC Mix 4.46-A
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	700.08
W/C ratio	0.46
Water lb/cu yd	322.04
Daravair M, oz/cwt	0.94
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	12.39
Correction for excess water on aggregates	
Coarse aggr. moisture, %	0.640
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0030
Coarse aggr. corr., lb/cu yd	3.90
Fine aggr. moisture, %	0.48
Fine aggr. absorption, %	0.30
Fine aggr. correction coeff.	0.0018
Fine aggr. corr., lb	2.65
Excess water correction, lb/cu yd	6.55
Batch	
Coarse, lb	129.69
Fine, lb	149.77
Cement, lb	70.01
Water, lb	31.55
Daravair M, mL	19.5
Daratard 17, mL	62.1
ADVA 555, mL	256.6

Table A.3 Batch Weights for Mitchell Precast Mix (continued)

Mix date	8/22/2006
Mix ID	8/22/06-3
Mix description	M-PC Mix 4.46-B
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	700.08
W/C ratio	0.46
Water lb/cu yd	322.04
Daravair M, oz/cwt	0.94
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	12.39
Correction for excess water on aggregates	
Coarse aggr. moisture, %	0.640
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0030
Coarse aggr. corr., lb/cu yd	3.90
Fine aggr. moisture, %	0.48
Fine aggr. absorption, %	0.30
Fine aggr. correction coeff.	0.0018
Fine aggr. corr., lb	2.65
Excess water correction, lb/cu yd	6.55
Batch	
Coarse, lb	129.69
Fine, lb	149.77
Cement, lb	70.01
Water, lb	31.55
Daravair M, mL	19.5
Daratard 17, mL	62.1
ADVA 555, mL	256.6

Table A.4 Batch Weights for Mitchell Cast-In-Place Mix

Mix date	8/17/2006
Mix ID	8/17/06-2
Mix description	M-CIP Mix 3.42-C
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	738
W/C ratio	0.42
Water lb/cu yd	309.96
Daravair M, oz/cwt	0.99
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	13.77
Correction for excess water on aggregates	
Coarse aggr. moisture, %	0.853
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0051
Coarse aggr. corr., lb/cu yd	6.64
Fine aggr. moisture, %	0.47
Fine aggr. absorption, %	0.32
Fine aggr. correction coeff.	0.0015
Fine aggr. corr., lb	2.23
Excess water correction, lb/cu yd	8.87
Batch	
Coarse, lb	129.96
Fine, lb	149.72
Cement, lb	73.80
Water, lb	30.11
Daravair M, mL	21.6
Daratard 17, mL	65.5
ADVA 555, mL	300.5

Table A.4 Batch Weights for Mitchell Cast-In-Place Mix (continued)

Mix date	8/17/2006
Mix ID	8/17/06-3
Mix description	M-CIP Mix 3.42-D
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	738
W/C ratio	0.42
Water lb/cu yd	309.96
Daravair M, oz/cwt	0.99
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	13.77
Correction for excess water on aggregates	
Coarse aggr. moisture, %	0.853
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0051
Coarse aggr. corr., lb/cu yd	6.64
Fine aggr. moisture, %	0.47
Fine aggr. absorption, %	0.32
Fine aggr. correction coeff.	0.0015
Fine aggr. corr., lb	2.23
Excess water correction, lb/cu yd	8.87
Batch	
Coarse, lb	129.96
Fine, lb	149.72
Cement, lb	73.80
Water, lb	30.11
Daravair M, mL	21.6
Daratard 17, mL	65.5
ADVA 555, mL	300.5

Table A.4 Batch Weights for Mitchell Cast-In-Place Mix (continued)

Mix date	8/18/2006
Mix ID	8/18/06-1
Mix description	M-CIP Mix 3.38-A
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	780.38
W/C ratio	0.38
Water lb/cu yd	296.54
Daravair M, oz/cwt	0.99
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	13.77
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.108
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0077
Coarse aggr. corr., lb/cu yd	9.93
Fine aggr. moisture, %	0.62
Fine aggr. absorption, %	0.32
Fine aggr. correction coeff.	0.0030
Fine aggr. corr., lb	4.47
Excess water correction, lb/cu yd	14.40
Batch	
Coarse, lb	130.29
Fine, lb	149.95
Cement, lb	78.04
Water, lb	28.21
Daravair M, mL	22.8
Daratard 17, mL	69.2
ADVA 555, mL	317.8

Table A.4 Batch Weights for Mitchell Cast-In-Place Mix (continued)

Mix date	8/18/2006
Mix ID	8/18/06-2
Mix description	M-CIP Mix 3.38-B
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	780.38
W/C ratio	0.38
Water lb/cu yd	296.54
Daravair M, oz/cwt	0.99
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	13.77
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.108
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0077
Coarse aggr. corr., lb/cu yd	9.93
Fine aggr. moisture, %	0.62
Fine aggr. absorption, %	0.32
Fine aggr. correction coeff.	0.0030
Fine aggr. corr., lb	4.47
Excess water correction, lb/cu yd	14.40
Batch	
Coarse, lb	130.29
Fine, lb	149.95
Cement, lb	78.04
Water, lb	28.21
Daravair M, mL	22.8
Daratard 17, mL	69.2
ADVA 555, mL	317.8

Table A.4 Batch Weights for Mitchell Cast-In-Place Mix (continued)

Mix date	8/19/2006
Mix ID	8/19/06-1
Mix description	M-CIP Mix 3.46-A
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	700.08
W/C ratio	0.46
Water lb/cu yd	322.04
Daravair M, oz/cwt	0.99
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	13.77
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.057
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0072
Coarse aggr. corr., lb/cu yd	9.28
Fine aggr. moisture, %	0.75
Fine aggr. absorption, %	0.32
Fine aggr. correction coeff.	0.0043
Fine aggr. corr., lb	6.38
Excess water correction, lb/cu yd	15.66
Batch	
Coarse, lb	130.23
Fine, lb	150.14
Cement, lb	70.01
Water, lb	30.64
Daravair M, mL	20.5
Daratard 17, mL	62.1
ADVA 555, mL	285.1

Table A.4 Batch Weights for Mitchell Cast-In-Place Mix (continued)

Mix date	8/19/2006
Mix ID	8/19/06-2
Mix description	M-CIP Mix 3.46-B
Batch size, cu yd	0.1
Mix design	
Coarse, lb/cu yd	1293
Fine, lb/cu yd	1495
Cement, lb/cu yd	700.08
W/C ratio	0.46
Water lb/cu yd	322.04
Daravair M, oz/cwt	0.99
Daratard 17, oz/cwt	3.00
ADVA 555, oz/cwt	13.77
Correction for excess water on aggregates	
Coarse aggr. moisture, %	1.057
Coarse aggr. absorption, %	0.338
Coarse aggr. correction coeff.	0.0072
Coarse aggr. corr., lb/cu yd	9.28
Fine aggr. moisture, %	0.75
Fine aggr. absorption, %	0.32
Fine aggr. correction coeff.	0.0043
Fine aggr. corr., lb	6.38
Excess water correction, lb/cu yd	15.66
Batch	
Coarse, lb	130.23
Fine, lb	150.14
Cement, lb	70.01
Water, lb	30.64
Daravair M, mL	20.5
Daratard 17, mL	62.1
ADVA 555, mL	285.1

APPENDIX B: TEST DATA

Table B.1 ASTM C 29 for Rapid City Limestone

ASTM C 29, "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate"

Test sample
Pete Lien / Rapid City 3/8" Limestone

Data	
Mass of measure (kg) =	3.52
Mass of measure + water (kg) =	10.52
Mass of water (kg) =	7
Water temperature (°F) =	80
Water density at this temperature (kg/m^3) =	996.59
Volume of measure (m^3) =	0.007024
Mass of measure (kg) =	3.52
Mass of aggregate + measure (kg) =	14.5
Mass of aggregate sample (kg) =	10.98
Bulk density of sample (kg/m^3) =	1563
Bulk density of sample (lb/ft^3) =	97.6

Summary of results	
Bulk density of sample (kg/m^3) =	1563
Bulk density of sample (lb/ft^3) =	97.6

Table B.2 ASTM C 29 for Sioux Falls Quartzite

ASTM C29, "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate"

Test sample
Sioux Falls Quarry / Sioux Falls Quartzite

Data

Mass of measure (kg) =	3.52
Mass of measure + water (kg) =	10.53
Mass of water (kg) =	7.01
Water temperature (ºF) =	75
Water density at this temperature (kg/m^3) =	997.32
Volume of measure (m^3) =	0.007029

Mass of measure (kg) =	3.52
Mass of aggregate + measure (kg) =	15.30
Mass of aggregate sample (kg) =	11.78
Bulk density of sample (kg/m^3) =	1676
Bulk density of sample (lb/ft^3) =	104.6

Summary of results

Bulk density of sample (kg/m^3) =	1676
Bulk density of sample (lb/ft^3) =	104.6

Table B.3 ASTM C 29 for Rapid City Sand

ASTM C 29, "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate"

Test sample
Birdsall / Creston Sand

Data	
Mass of measure (kg) =	3.52
Mass of measure + water (kg) =	10.52
Mass of water (kg) =	7
Water temperature (ºF) =	80
Water density at this temperature (kg/m^3) =	996.59
Volume of measure (m^3) =	0.007024
Mass of measure (kg) =	3.52
Mass of aggregate + measure (kg) =	15.01
Mass of aggregate sample (kg) =	11.49
Bulk density of sample (kg/m^3) =	1636
Bulk density of sample (lb/ft^3) =	102.1

Summary of results	
Bulk density of sample (kg/m^3) =	1636
Bulk density of sample (lb/ft^3) =	102.1

Table B.4 ASTM C 29 for Mitchell Sand 1

ASTM C 29, "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate"

Test sample
Bitterman / Mitchell Sand

Data	
Mass of measure (kg) =	3.52
Mass of measure + water (kg) =	10.53
Mass of water (kg) =	7.01
Water temperature (ºF) =	75
Water density at this temperature (kg/m^3) =	997.32
Volume of measure (m^3) =	0.007029
Mass of measure (kg) =	3.52
Mass of aggregate + measure (kg) =	15.95
Mass of aggregate sample (kg) =	12.43
Bulk density of sample (kg/m^3) =	1768
Bulk density of sample (lb/ft^3) =	110.4

Summary of results	
Bulk density of sample (kg/m^3) =	1768
Bulk density of sample (lb/ft^3) =	110.4

Table B.5 ASTM C 29 for Mitchell Sand 2

ASTM C 29, "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate"

Test sample
Opperman / Ft. Randall Sand

Data	
Mass of measure (kg) =	3.52
Mass of measure + water (kg) =	10.53
Mass of water (kg) =	7.01
Water temperature (ºF) =	75
Water density at this temperature (kg/m^3) =	997.32
Volume of measure (m^3) =	0.007029
Mass of measure (kg) =	3.52
Mass of aggregate + measure (kg) =	16.12
Mass of aggregate sample (kg) =	12.6
Bulk density of sample (kg/m^3) =	1793
Bulk density of sample (lb/ft^3) =	111.9

Summary of results	
Bulk density of sample (kg/m^3) =	1793
Bulk density of sample (lb/ft^3) =	111.9

Table B.6 ASTM C 127 for Rapid City Limestone

ASTM C 127, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate"

Test Sample
Pete Lien / Rapid City 3/8" Limestone

Data	
Mass of bowl, g =	282.40
Mass of bowl + SSD aggr., g =	2490.26
Mass of bowl + oven dry aggr., g =	2482.20
Mass of SSD aggr., g =	2207.86
Mass of oven dry aggr., g =	2199.80
Absorption, % =	0.37
Mass of oven dry sample in air, g =	2199.80
Mass of SSD sample in air, g =	2207.86
Apparent mass of sieve in water, g =	499.75
Apparent mass of sieve + sample in water, g =	1876.10
Apparent mass of saturated sample in water, g =	1376.35
Specific gravity of SSD sample =	2.66
Density, kg/m^3 =	2648.60
Density, lb/ft^3 =	165.34

Summary of Results	
Specific gravity of SSD sample =	2.66
Density, kg/m^3 =	2649
Density, lb/ft^3 =	165.3
Absorption, % =	0.37

Table B.6 ASTM C 127 for Rapid City Limestone (continued)

ASTM C 127, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption Coarse Aggregate"

Test Sample
Pete Lien / Rapid City 3/8" Limestone

Data	
Mass of bowl, g =	282.11
Mass of bowl + SSD aggr., g =	2490.79
Mass of bowl + oven dry aggr., g =	2482.51
Mass of SSD aggr., g =	2208.68
Mass of oven dry aggr., g =	2200.40
Absorption, % =	0.38
Mass of oven dry sample in air, g =	2200.40
Mass of SSD sample in air, g =	2208.68
Apparent mass of sieve in water, g =	484.55
Apparent mass of sieve + sample in water, g =	1846.94
Apparent mass of saturated sample in water, g =	1362.39
Specific gravity of SSD sample =	2.61
Density, kg/m^3 =	2603
Density, lb/ft^3 =	162.5

Summary of Results	
Specific gravity of SSD sample =	2.61
Density, kg/m^3 =	2603
Density, lb/ft^3 =	162.5
Absorption, % =	0.38

Table B.6 ASTM C 127 for Rapid City Limestone (continued)

ASTM C 127, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption Coarse Aggregate"

Test Sample
Pete Lien / Rapid City 3/8" Limestone

Data	
Mass of bowl, g =	231.10
Mass of bowl + SSD aggr., g =	1518.16
Mass of bowl + oven dry aggr., g =	1514.02
Mass of SSD aggr., g =	1287.06
Mass of oven dry aggr., g =	1282.92
Absorption, % =	0.32
Mass of oven dry sample in air, g =	1282.92
Mass of SSD sample in air, g =	1287.06
Apparent mass of sieve in water, g =	484.55
Apparent mass of sieve + sample in water, g =	1291.45
Apparent mass of saturated sample in water, g =	806.90
Specific gravity of SSD sample =	2.68
Density, kg/m^3 =	2674
Density, lb/ft^3 =	166.9

Summary of Results	
Specific gravity of SSD sample =	2.68
Density, kg/m^3 =	2674
Density, lb/ft^3 =	166.9
Absorption, % =	0.32

Table B.7 ASTM C 127 for Sioux Falls Quartzite

ASTM C 127, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate"

Test Sample
Concrete Materials Quartzite

Data	
Mass of bowl, g =	176.69
Mass of bowl + SSD aggr., g =	1737.11
Mass of bowl + oven dry aggr., g =	1731.99
Mass of SSD aggr., g =	1560.42
Mass of oven dry aggr., g =	1555.30
Absorption, % =	0.33
Mass of oven dry sample in air, g =	1555.30
Mass of SSD sample in air, g =	1560.42
Apparent mass of sieve in water, g =	483.11
Apparent mass of sieve + sample in water, g =	1450.75
Apparent mass of saturated sample in water, g =	967.64
Specific gravity of SSD sample =	2.63
Density, kg/m^3 =	2625.80
Density, lb/ft^3 =	163.92

Summary of Results	
Specific gravity of SSD sample =	2.63
Density, kg/m^3 =	2626
Density, lb/ft^3 =	163.9
Absorption, % =	0.33

Table B.7 ASTM C 127 for Sioux Falls Quartzite (continued)

ASTM C 127, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate"

Test Sample
Concrete Materials Quartzite

Data	
Mass of bowl, g =	287.93
Mass of bowl + SSD aggr., g =	2580.20
Mass of bowl + oven dry aggr., g =	2571.58
Mass of SSD aggr., g =	2292.27
Mass of oven dry aggr., g =	2283.65
Absorption, % =	0.38
Mass of oven dry sample in air, g =	2283.65
Mass of SSD sample in air, g =	2292.27
Apparent mass of sieve in water, g =	483.25
Apparent mass of sieve + sample in water, g =	1903.36
Apparent mass of saturated sample in water, g =	1420.11
Specific gravity of SSD sample =	2.63
Density, kg/m^3 =	2621.70
Density, lb/ft^3 =	163.66

Summary of Results	
Specific gravity of SSD sample =	2.63
Density, kg/m^3 =	2622
Density, lb/ft^3 =	163.7
Absorption, % =	0.38

Table B.7 ASTM C 127 for Sioux Falls Quartzite (continued)

ASTM C 127, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate"

Test Sample
Concrete Materials Quartzite

Data	
Mass of bowl, g =	231.18
Mass of bowl + SSD aggr., g =	1866.75
Mass of bowl + oven dry aggr., g =	1861.76
Mass of SSD aggr., g =	1635.57
Mass of oven dry aggr., g =	1630.58
Absorption, % =	0.31
Mass of oven dry sample in air, g =	1630.58
Mass of SSD sample in air, g =	1635.57
Apparent mass of sieve in water, g =	483.18
Apparent mass of sieve + sample in water, g =	1498.93
Apparent mass of saturated sample in water, g =	1015.75
Specific gravity of SSD sample =	2.64
Density, kg/m^3 =	2632.19
Density, lb/ft^3 =	164.32

Summary of Results	
Specific gravity of SSD sample =	2.64
Density, kg/m^3 =	2632
Density, lb/ft^3 =	164.3
Absorption, % =	0.31

Table B.8 ASTM C 128 for Rapid City Sand

ASTM C 128, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate"

Test Sample
Birdsall / Creston Sand

Data	
Mass of flask, g =	189.52
Mass of flask + water to calibration, g =	688.08
Mass of flask + SSD aggr., g =	609.35
Mass of flask + SSD aggr. + water, g =	948.47
Mass of SSD aggr., g =	419.83
Specific gravity of SSD sample =	2.63
Density, kg/m^3 =	2626.57
Density, lb/ft^3 =	163.97
Mass of flask, g =	188.91
Mass of flask + water to calibration, g =	687.22
Mass of flask + SSD aggr., g =	626.63
Mass of flask + SSD aggr. + water, g =	959.45
Mass of SSD aggr., g =	437.72
Specific gravity of SSD sample =	2.64
Density, kg/m^3 =	2638.38
Density, lb/ft^3 =	164.70
Mass of bowl, g =	493.65
Mass of bowl + oven dry aggr., g =	1342.05
Mass of oven dry aggr., g =	848.40
Mass of SSD aggr., g =	857.55
Absorption, % =	1.08

Summary of Results	
Specific gravity of SSD sample =	2.64
Density, kg/m^3 =	2632
Density, lb/ft^3 =	164.3
Absorption, % =	1.08

Table B.8 ASTM C 128 for Rapid City Sand (continued)

ASTM C 128, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate"

Test Sample
Birdsall / Creston Sand

Data

Mass of flask, g =	98.09
Mass of flask + water to calibration, g =	347.63
Mass of flask + SSD aggr., g =	328.58
Mass of flask + SSD aggr. + water, g =	490.77
Mass of SSD aggr., g =	230.49
Specific gravity =	2.64
Density, kg/m^3 =	2632.10
Density, lb/ft^3 =	164.31
Mass of flask, g =	94.99
Mass of flask + water to calibration, g =	348.07
Mass of flask + SSD aggr., g =	340.62
Mass of flask + SSD aggr. + water, g =	500.56
Mass of SSD aggr., g =	245.63
Specific gravity =	2.64
Density, kg/m^3 =	2630.62
Density, lb/ft^3 =	164.22
Mass of bowl, g =	231.29
Mass of bowl + oven dry aggr., g =	702.50
Mass of oven dry aggr., g =	471.21
Mass of SSD aggr., g =	476.12
Absorption, % =	1.04

Summary of Results

Specific gravity =	2.64
Density, kg/m^3 =	2631
Density, lb/ft^3 =	164.3
Absorption, % =	1.04

Table B.8 ASTM C 128 for Rapid City Sand (continued)

ASTM C 128, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate"

Test Sample
Birdsall / Creston Sand

Data	
Mass of flask, g =	191.39
Mass of flask + water to calibration, g =	690.00
Mass of flask + SSD aggr., g =	653.05
Mass of flask + SSD aggr. + water, g =	976.13
Mass of SSD aggr., g =	461.66
Specific gravity of SSD sample =	2.63
Density, kg/m^3 =	2623.52
Density, lb/ft^3 =	163.78
Mass of flask, g =	190.25
Mass of flask + water to calibration, g =	688.76
Mass of flask + SSD aggr., g =	655.50
Mass of flask + SSD aggr. + water, g =	977.01
Mass of SSD aggr., g =	465.25
Specific gravity of SSD sample =	2.63
Density, kg/m^3 =	2622
Density, lb/ft^3 =	163.7
Mass of bowl, g =	355.96
Mass of bowl + oven dry aggr., g =	1272.26
Mass of oven dry aggr., g =	916.30
Mass of SSD aggr., g =	926.91
Absorption, % =	1.16

Summary of Results	
Specific gravity of SSD sample =	2.63
Density, kg/m^3 =	2623
Density, lb/ft^3 =	163.7
Absorption, % =	1.2

Table B.9 ASTM C 128 for Mitchell Sand 1

ASTM C 128, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate"

Test Sample
Bitterman / Mitchell Sand

Data	
Mass of flask, g =	189.56
Mass of flask + water to calibration, g =	688.78
Mass of flask + SSD aggr., g =	551.12
Mass of flask + SSD aggr. + water, g =	911.79
Mass of SSD aggr., g =	361.56
Specific gravity of SSD sample =	2.61
Density, kg/m^3 =	2603.08
Density, lb/ft^3 =	162.50
Mass of flask, g =	188.90
Mass of flask + water to calibration, g =	690.64
Mass of flask + SSD aggr., g =	679.20
Mass of flask + SSD aggr. + water, g =	990.32
Mass of SSD aggr., g =	490.30
Specific gravity of SSD sample =	2.57
Density, kg/m^3 =	2565.70
Density, lb/ft^3 =	160.17
Mass of bowl, g =	355.98
Mass of bowl + oven dry aggr., g =	1204.95
Mass of oven dry aggr., g =	848.97
Mass of SSD aggr., g =	851.86
Absorption, % =	0.34

Summary of Results	
Specific gravity of SSD sample =	2.59
Density, kg/m^3 =	2584
Density, lb/ft^3 =	161.3
Absorption, % =	0.34

Table B.9 ASTM C 128 for Mitchell Sand 1 (continued)

ASTM C 128, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate"

Test Sample
Bitterman / Mitchell Sand

Data

Mass of flask, g = 191.38
Mass of flask + water to calibration, g = 690.21
Mass of flask + SSD aggr., g = 607.46
Mass of flask + SSD aggr. + water, g = 947.04
Mass of SSD aggr., g = 416.08
Specific gravity of SSD sample = 2.61
Density, kg/m^3 = 2606.22
Density, lb/ft^3 = 162.70

Mass of flask, g = 190.34
Mass of flask + water to calibration, g = 688.99
Mass of flask + SSD aggr., g = 611.05
Mass of flask + SSD aggr. + water, g = 948.96
Mass of SSD aggr., g = 420.71
Specific gravity of SSD sample = 2.62
Density, kg/m^3 = 2610.79
Density, lb/ft^3 = 162.98

Mass of bowl, g = 227.55
Mass of bowl + oven dry aggr., g = 1062.18
Mass of oven dry aggr., g = 834.63
Mass of SSD aggr., g = 836.79
Absorption, % = 0.26

Summary of Results

Specific gravity of SSD sample = 2.62
Density, kg/m^3 = 2609
Density, lb/ft^3 = 162.8
Absorption, % = 0.26

Table B.9 ASTM C 128 for Mitchell Sand 1 (continued)

ASTM C 128, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate"

Test Sample
Bitterman / Mitchell Sand

Data	
Mass of flask, g =	189.52
Mass of flask + water to calibration, g =	688.76
Mass of flask + SSD aggr., g =	716.84
Mass of flask + SSD aggr. + water, g =	1013.35
Mass of SSD aggr., g =	527.32
Specific gravity of SSD sample =	2.60
Density, kg/m^3 =	2594.59
Density, lb/ft^3 =	161.97
Mass of flask, g =	188.92
Mass of flask + water to calibration, g =	687.95
Mass of flask + SSD aggr., g =	611.05
Mass of flask + SSD aggr. + water, g =	948.96
Mass of SSD aggr., g =	422.13
Specific gravity of SSD sample =	2.62
Density, kg/m^3 =	2613.42
Density, lb/ft^3 =	163.15
Mass of bowl, g =	355.71
Mass of bowl + oven dry aggr., g =	x
Mass of oven dry aggr., g =	x
Mass of SSD aggr., g =	949.45
Absorption, % =	x

Summary of Results	
Specific gravity of SSD sample =	2.61
Density, kg/m^3 =	2604
Density, lb/ft^3 =	162.6
Absorption, % =	x

Table B.10 ASTM C 128 for Mitchell Sand 2

ASTM C 128, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate"

Test Sample
Opperman / Fort Randall Sand

Data	
Mass of flask, g =	193.18
Mass of flask + water to calibration, g =	692.03
Mass of flask + SSD aggr., g =	542.44
Mass of flask + SSD aggr. + water, g =	907.04
Mass of SSD aggr., g =	349.26
Specific gravity of SSD sample =	2.60
Density, kg/m^3 =	2595.06
Density, lb/ft^3 =	162.00
Mass of flask, g =	190.31
Mass of flask + water to calibration, g =	688.66
Mass of flask + SSD aggr., g =	691.49
Mass of flask + SSD aggr. + water, g =	997.42
Mass of SSD aggr., g =	501.18
Specific gravity of SSD sample =	2.60
Density, kg/m^3 =	2598.10
Density, lb/ft^3 =	162.19
Mass of bowl, g =	356.08
Mass of bowl + oven dry aggr., g =	1203.68
Mass of oven dry aggr., g =	847.60
Mass of SSD aggr., g =	850.44
Absorption, % =	0.34

Summary of Results	
Specific gravity of SSD sample =	2.60
Density, kg/m^3 =	2597
Density, lb/ft^3 =	162.1
Absorption, % =	0.34

Table B.10 ASTM C 128 for Mitchell Sand 2 (continued)

ASTM C 128, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate"

Test Sample
Opperman / Fort Randall Sand

Data	
Mass of flask, g =	191.44
Mass of flask + water to calibration, g =	689.86
Mass of flask + SSD aggr., g =	649.00
Mass of flask + SSD aggr. + water, g =	972.60
Mass of SSD aggr., g =	457.56
Specific gravity of SSD sample =	2.62
Density, kg/m^3 =	2610.78
Density, lb/ft^3 =	162.98
Mass of flask, g =	188.88
Mass of flask + water to calibration, g =	687.69
Mass of flask + SSD aggr., g =	595.07
Mass of flask + SSD aggr. + water, g =	938.13
Mass of SSD aggr., g =	406.19
Specific gravity of SSD sample =	2.61
Density, kg/m^3 =	2601.44
Density, lb/ft^3 =	162.40
Mass of bowl, g =	227.95
Mass of bowl + oven dry aggr., g =	1089.00
Mass of oven dry aggr., g =	861.05
Mass of SSD aggr., g =	863.75
Absorption, % =	0.31

Summary of Results	
Specific gravity of SSD sample =	2.61
Density, kg/m^3 =	2606
Density, lb/ft^3 =	162.7
Absorption, % =	0.31

Table B.11 ASTM C 136 for Rapid City Limestone

ASTM C 136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates"

Test Sample
Pete Lien / Rapid City 3/8" Limestone

Sieve	Size (in)	Sieve Wt. Only (kg)	Sieve + Retained Sample Wt. (kg)	Retained Sample Wt. (kg)	Percent Retained on Sieve (%)	Percent Passing Sieve (%)
1"	1	7.22	7.22	0.00	0.0	100.0
3/4"	0.75	7.22	7.22	0.00	0.0	100.0
1/2"	0.5	7.34	7.34	0.00	0.0	100.0
3/8"	0.375	7.18	7.22	0.04	3.4	96.6
No. 4	0.1870079	7.34	8.37	1.03	87.3	9.3
Pan	0	7.28	7.39	0.11	9.3	0.0

Table B.12 ASTM C 136 for Sioux Falls Quartzite

ASTM C 136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates"

Test Sample
Concrete Materials Quartzite

Sieve	Size (in)	Sieve Wt. Only (kg)	Sieve + Retained Sample Wt. (kg)	Retained Sample Wt. (kg)	Percent Retained on Sieve (%)	Percent Passing Sieve (%)	Min. SD DOT % Passing Req't (%)	Max. SD DOT % Passing Req't (%)
1"	1	7.24	7.24	0.00	0.0	100.0		
3/4"	0.75	7.22	7.22	0.00	0.0	100.0	100	
1/2"	0.5	7.34	7.37	0.03	0.3	99.7	90	100
3/8"	0.375	7.17	10.14	2.97	32.5	67.2	70	90
No. 4	0.1870079	7.28	11.39	4.11	44.9	22.3	0	30
Pan	0	7.28	9.32	2.04	22.3	0.0		

Total Retained 9.15 100.0

Table B.13 ASTM C 136 for Rapid City Sand

ASTM C 136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates"

Test Sample
Birdsall / Creston Sand

Sieve	Size (μm)	Sieve Wt. Only (g)	Sieve + Retained Sample Wt. (g)	Retained Sample Wt. (g)	Percent Retained on Sieve (%)	Percent Passing Sieve (%)	Min. SD DOT % Passing Req't (%)	Max. SD DOT % Passing Req't (%)
3/8"	9500			0.00	0.0	100.0	100	100
No. 4	4750	765.17	771.74	6.57	0.9	99.1	95	100
No. 8	2360	686.73	768.04	81.31	11.1	88.0		
No. 16	1180	646.91	810.89	163.98	22.5	65.5	45	85
No. 30	600	591.36	819.52	228.16	31.3	34.3		
No. 50	300	548.39	693.08	144.69	19.8	14.4	10	30
No. 100	150	521.93	598.96	77.03	10.6	3.9	2	10
No. 200	75	513.73	531.25	17.52	2.4	1.5		
Pan	0	492.60	493.00	0.40	1.5	0.0		
Wash	0			10.42				

Total Sample Weight 730.08 100.0
Sample Wt. Before Washing & Sieving 729.93
Percent Difference Between Sample Wt. Before Sieving and Wt. Retained on Sieves (%) 0.02

Sieve	Size (μm)	Percent Retained on Sieve (%)	Cumulative Percent Retained on Sieve (%)
3/8"	9500	0.0	0.0
No. 4	4750	0.9	0.9
No. 8	2360	11.1	12.0
No. 16	1180	22.5	34.5
No. 30	600	31.3	65.7
No. 50	300	19.8	85.6
No. 100	150	10.6	96.1
No. 200	75	2.4	98.5
Pan	0	1.5	100.0
Wash	0		

Fineness Modulus 2.95

Table B.14 ASTM C 136 for Mitchell Sand 1

ASTM C 136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates"

Test Sample
"Mitchell" Precast Sand

Sieve	Size (μm)	Sieve Wt. Only (g)	Sieve + Retained Sample Wt. (g)	Retained Sample Wt. (g)	Percent Retained on Sieve (%)	Percent Passing Sieve (%)	Min. SD DOT % Passing Req't (%)	Max. SD DOT % Passing Req't (%)
3/8"	9500			0.00	0.0	100.0	100	100
No. 4	4750	765.08	796.67	31.59	3.2	96.8	95	100
No. 8	2360	686.97	749.03	62.06	6.2	90.6		
No. 16	1180	647.04	776.17	129.13	12.9	77.7	45	85
No. 30	600	591.36	847.51	256.15	25.7	52.0		
No. 50	300	548.38	877.62	329.24	33.0	19.0	10	30
No. 100	150	522.56	679.66	157.10	15.8	3.2	2	10
No. 200	75	513.81	531.62	17.81	1.8	1.4		
Pan	0	492.51	492.74	0.23	1.4	0.0		
Wash	0			13.96				

Total Sample Weight 997.27 100.0
Sample Wt. Before Washing & Sieving 996.49
Percent Difference Between Sample Wt. Before Sieving and Wt. Retained on Sieves (%) 0.08

Sieve	Size (μm)	Percent Retained on Sieve (%)	Cumulative Percent Retained on Sieve (%)
3/8"	9500	0.0	0.0
No. 4	4750	3.2	3.2
No. 8	2360	6.2	9.4
No. 16	1180	12.9	22.3
No. 30	600	25.7	48.0
No. 50	300	33.0	81.0
No. 100	150	15.8	96.8
No. 200	75	1.8	98.6
Pan	0	1.4	100.0
Wash	0		

Fineness Modulus 2.61

Table B.15 ASTM C 136 for Mitchell Sand 2

ASTM C 136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates"

Test Sample
"Mitchell" Cast-In-Place Sand

Sieve	Size (µm)	Sieve Wt. Only (g)	Sieve + Retained Sample Wt. (g)	Retained Sample Wt. (g)	Percent Retained on Sieve (%)	Percent Passing Sieve (%)	Min. SD DOT % Passing Req't (%)	Max. SD DOT % Passing Req't (%)
3/8"	9500			0.00	0.0	100.0	100	100
No. 4	4750	765.07	804.18	39.11	2.9	97.1	95	100
No. 8	2360	687.02	806.62	119.60	8.9	88.2		
No. 16	1180	647.61	841.93	194.32	14.4	73.8	45	85
No. 30	600	591.26	891.53	300.27	22.3	51.5		
No. 50	300	548.63	952.90	404.27	30.0	21.5	10	30
No. 100	150	521.82	752.48	230.66	17.1	4.4	2	10
No. 200	75	513.73	556.19	42.46	3.2	1.2		
Pan	0	492.50	494.56	2.06	1.2	0.0		
Wash	0			14.46				

Total Sample Weight 1347.21 100.0

Sample Wt. Before Washing & Sieving 996.49

Percent Difference Between Sample Wt. Before Sieving and Wt. Retained on Sieves (%) 35.20

Sieve	Size (µm)	Percent Retained on Sieve (%)	Cumulative Percent Retained on Sieve (%)
3/8"	9500	0.0	0.0
No. 4	4750	2.9	2.9
No. 8	2360	8.9	11.8
No. 16	1180	14.4	26.2
No. 30	600	22.3	48.5
No. 50	300	30.0	78.5
No. 100	150	17.1	95.6
No. 200	75	3.2	98.8
Pan	0	1.2	100.0
Wash	0		

Fineness Modulus 2.64

Table B.16 Fresh Concrete Tests for Rapid City Precast Mix, W/C = 0.38

Fresh concrete properties	
Mix ID	7/13/06-2
	1.38-A
Temperature	
Temperature, °F	82
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	43.44
Unit weight, lb/ft^3 =	143.9
Air content	
Air, % =	7.0
Slump	
Diameter 1, in =	21
Diameter 2, in =	21
Average diameter, in =	21.0
T_{20}, sec =	3.07
VSI =	0
J-ring	
Diameter 1, in =	18.75
Diameter 2, in =	19
Average diameter, in =	18.9
T_{20}, sec =	x
L-box	
H1, in =	5
H2, in =	2
H2/H1 =	0.4
Column segregation	
Coarse mass in top, g =	8.28
Coarse mass in bottom, g =	8.96
% difference, % =	7.9

Table B.16 Fresh Concrete Tests for Rapid City Precast Mix, W/C = 0.38 (cont.)

Fresh concrete properties	
Mix ID	7/14/06-1
	1.38-B
Temperature	
Temperature, °F	74
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.76
Unit weight, lb/ft^3 =	141.1
Air content	
Air, % =	8.0
Slump	
Diameter 1, in =	21.25
Diameter 2, in =	22.5
Average diameter, in =	21.9
T_{20}, sec =	1.87
VSI =	0
J-ring	
Diameter 1, in =	21
Diameter 2, in =	21
Average diameter, in =	21.0
T_{20}, sec =	3.79
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.17 Fresh Concrete Tests for Rapid City Precast Mix, W/C = 0.42

Fresh concrete properties	
Mix ID	7/12/06-1
	1.42-D
Temperature	
Temperature, °F	81.5
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	43.12
Unit weight, lb/ft^3 =	142.6
Air content	
Air, % =	7.0
Slump	
Diameter 1, in =	21
Diameter 2, in =	20.75
Average diameter, in =	20.9
T_{20}, sec =	1.7
VSI =	0
J-ring	
Diameter 1, in =	22
Diameter 2, in =	21.95
Average diameter, in =	22.0
T_{20}, sec =	1.99
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.17 Fresh Concrete Tests for Rapid City Precast Mix, W/C = 0.42 (cont.)

Fresh concrete properties	
Mix ID	7/13/06-1
	1.42-E
Temperature	
Temperature, °F	76.5
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	43.18
Unit weight, lb/ft^3 =	142.8
Air content	
Air, % =	7.2
Slump	
Diameter 1, in =	23
Diameter 2, in =	23.5
Average diameter, in =	23.3
T_{20}, sec =	1.09
VSI =	0.5
J-ring	
Diameter 1, in =	23
Diameter 2, in =	21.75
Average diameter, in =	22.4
T_{20}, sec =	1.84
L-box	
H1, in =	4.375
H2, in =	1.75
H2/H1 =	0.4
Column segregation	
Coarse mass in top, g =	8.24
Coarse mass in bottom, g =	9.06
% difference, % =	9.5

Table B.18 Fresh Concrete Tests for Rapid City Precast Mix, W/C = 0.46

Fresh concrete properties	
Mix ID	7/17/06-1
	1.46-A
Temperature	
Temperature, °F	75.5
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.62
Unit weight, lb/ft^3 =	140.6
Air content	
Air, % =	7.2
Slump	
Diameter 1, in =	22
Diameter 2, in =	23
Average diameter, in =	22.5
T_{20}, sec =	0.9
VSI =	0.5
J-ring	
Diameter 1, in =	22
Diameter 2, in =	21.95
Average diameter, in =	22.0
T_{20}, sec =	1.99
L-box	
H1, in =	4.5
H2, in =	2.0625
H2/H1 =	0.458333333
Column segregation	
Coarse mass in top, g =	8.3
Coarse mass in bottom, g =	8.44
% difference, % =	1.7

Table B.18 Fresh Concrete Tests for Rapid City Precast Mix, W/C = 0.46 (cont.)

Fresh concrete properties	
Mix ID	7/17/06-2
	1.46-B
Temperature	
Temperature, °F	79
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.74
Unit weight, lb/ft^3 =	141.0
Air content	
Air, % =	6.0
Slump	
Diameter 1, in =	21.75
Diameter 2, in =	22
Average diameter, in =	21.9
T_{20}, sec =	1.89
VSI =	0
J-ring	
Diameter 1, in =	
Diameter 2, in =	
Average diameter, in =	0.0
T_{20}, sec =	
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.19 Fresh Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.38

Fresh concrete properties	
Mix ID	7/25/06-1
	2.38-B
Temperature	
Temperature, °F	80.5
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.94
Unit weight, lb/ft^3 =	141.9
Air content	
Air, % =	8.1
Slump	
Diameter 1, in =	19.25
Diameter 2, in =	19.25
Average diameter, in =	19.3
T_{20}, sec =	x
VSI =	0
J-ring	
Diameter 1, in =	17
Diameter 2, in =	17.25
Average diameter, in =	17.1
T_{20}, sec =	x
L-box	
H1, in =	x
H2, in =	
H2/H1 =	x
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.19 Fresh Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.38 (cont.)

Fresh concrete properties	
Mix ID	7/26/06-1
	2.38-C
Temperature	
Temperature, °F	79
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.94
Unit weight, lb/ft^3 =	141.9
Air content	
Air, % =	7.9
Slump	
Diameter 1, in =	19.5
Diameter 2, in =	19.25
Average diameter, in =	19.4
T_{20}, sec =	x
VSI =	0
J-ring	
Diameter 1, in =	16.5
Diameter 2, in =	17
Average diameter, in =	16.8
T_{20}, sec =	x
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	8.9
Coarse mass in bottom, g =	9.06
% difference, % =	1.8

Table B.20 Fresh Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.42

Fresh concrete properties	
Mix ID	7/19/06-2
	2.42-A
Temperature	
Temperature, °F	84.5
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.28
Unit weight, lb/ft^3 =	139.2
Air content	
Air, % =	8.1
Slump	
Diameter 1, in =	20
Diameter 2, in =	20.25
Average diameter, in =	20.1
T_{20}, sec =	1.51
VSI =	0
J-ring	
Diameter 1, in =	19
Diameter 2, in =	18.75
Average diameter, in =	18.9
T_{20}, sec =	x
L-box	
H1, in =	5.125
H2, in =	1.5
H2/H1 =	0.292682927
Column segregation	
Coarse mass in top, g =	8.62
Coarse mass in bottom, g =	9.28
% difference, % =	7.4

Table B.20 Fresh Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.42 (cont.)

Fresh concrete properties	
Mix ID	7/24/06-1
	2.42-B
Temperature	
Temperature, °F	80.5
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	41.86
Unit weight, lb/ft^3 =	137.5
Air content	
Air, % =	9.0
Slump	
Diameter 1, in =	21.5
Diameter 2, in =	21.75
Average diameter, in =	21.6
T_{20}, sec =	1.07
VSI =	0
J-ring	
Diameter 1, in =	20.25
Diameter 2, in =	20.25
Average diameter, in =	20.3
T_{20}, sec =	1.97
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.21 Fresh Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.46

Fresh concrete properties	
Mix ID	7/18/06-1
	2.46-A
Temperature	
Temperature, °F	79
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	41.88
Unit weight, lb/ft^3 =	137.6
Air content	
Air, % =	8.6
Slump	
Diameter 1, in =	20.25
Diameter 2, in =	20.75
Average diameter, in =	20.5
T_{20}, sec =	1.76
VSI =	0
J-ring	
Diameter 1, in =	19
Diameter 2, in =	19.25
Average diameter, in =	19.1
T_{20}, sec =	x
L-box	
H1, in =	4
H2, in =	1
H2/H1 =	0.25
Column segregation	
Coarse mass in top, g =	8.9
Coarse mass in bottom, g =	8.84
% difference, % =	-0.7

Table B.21 Fresh Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.46 (cont.)

Fresh concrete properties	
Mix ID	7/19/06-1
	2.46-B
Temperature	
Temperature, °F	80
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.74
Unit weight, lb/ft^3 =	141.0
Air content	
Air, % =	7.9
Slump	
Diameter 1, in =	23
Diameter 2, in =	22.5
Average diameter, in =	22.8
T_{20}, sec =	0.99
VSI =	0
J-ring	
Diameter 1, in =	22
Diameter 2, in =	21.5
Average diameter, in =	21.8
T_{20}, sec =	1.12
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.22 Fresh Concrete Tests for Mitchell Precast Mix, W/C = 0.38

Fresh concrete properties	
Mix ID	8/21/06-3
	4.38-A
Temperature	
Temperature, °F	86
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.64
Unit weight, lb/ft^3 =	140.6
Air content	
Air, % =	8.0
Slump	
Diameter 1, in =	20.5
Diameter 2, in =	21.25
Average diameter, in =	20.9
T_{20}, sec =	2.87
VSI =	0
J-ring	
Diameter 1, in =	18.5
Diameter 2, in =	19
Average diameter, in =	18.8
T_{20}, sec =	x
L-box	
H1, in =	5
H2, in =	1.5
H2/H1 =	0.3
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.22 Fresh Concrete Tests for Mitchell Precast Mix, W/C = 0.38 (cont.)

Fresh concrete properties	
Mix ID	8/22/06-1
	4.38-B
Temperature	
Temperature, °F	78
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42
Unit weight, lb/ft^3 =	138.1
Air content	
Air, % =	8.5
Slump	
Diameter 1, in =	21
Diameter 2, in =	20.75
Average diameter, in =	20.9
T_{20}, sec =	3.04
VSI =	0
J-ring	
Diameter 1, in =	19
Diameter 2, in =	19.25
Average diameter, in =	19.1
T_{20}, sec =	x
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	7.56
Coarse mass in bottom, g =	7.86
% difference, % =	3.9

Table B.23 Fresh Concrete Tests for Mitchell Precast Mix, W/C = 0.42

Fresh concrete properties	
Mix ID	8/21/06-2
	4.42-B
Temperature	
Temperature, °F	84
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.56
Unit weight, lb/ft^3 =	140.3
Air content	
Air, % =	7.1
Slump	
Diameter 1, in =	22.75
Diameter 2, in =	23.5
Average diameter, in =	23.1
T_{20}, sec =	1.36
VSI =	0
J-ring	
Diameter 1, in =	19.5
Diameter 2, in =	20.75
Average diameter, in =	20.1
T_{20}, sec =	4.02
L-box	
H1, in =	4.375
H2, in =	2.125
H2/H1 =	0.485714286
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.23 Fresh Concrete Tests for Mitchell Precast Mix, W/C = 0.42 (cont.)

Fresh concrete properties	
Mix ID	8/23/06-1
	4.42-C
Temperature	
Temperature, °F	81
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42
Unit weight, lb/ft^3 =	138.1
Air content	
Air, % =	7.8
Slump	
Diameter 1, in =	21
Diameter 2, in =	21
Average diameter, in =	21.0
T_{20}, sec =	2.14
VSI =	0
J-ring	
Diameter 1, in =	18.75
Diameter 2, in =	18
Average diameter, in =	18.4
T_{20}, sec =	x
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	7.34
Coarse mass in bottom, g =	7.64
% difference, % =	4.0

Table B.24 Fresh Concrete Tests for Mitchell Precast Mix, W/C = 0.46

Fresh concrete properties	
Mix ID	8/22/06-2
	4.46-A
Temperature	
Temperature, °F	84.5
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.58
Unit weight, lb/ft^3 =	140.4
Air content	
Air, % =	5.5
Slump	
Diameter 1, in =	24.25
Diameter 2, in =	24.5
Average diameter, in =	24.4
T_{20}, sec =	0.89
VSI =	0.5
J-ring	
Diameter 1, in =	22.5
Diameter 2, in =	22
Average diameter, in =	22.3
T_{20}, sec =	1.97
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	6.92
Coarse mass in bottom, g =	6.84
% difference, % =	-1.2

Table B.24 Fresh Concrete Tests for Mitchell Precast Mix, W/C = 0.46 (cont.)

Fresh concrete properties	
Mix ID	8/22/06-3
	4.46-B
Temperature	
Temperature, °F	86
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	43.12
Unit weight, lb/ft^3 =	142.6
Air content	
Air, % =	4.8
Slump	
Diameter 1, in =	24.5
Diameter 2, in =	25
Average diameter, in =	24.8
T_{20}, sec =	0.84
VSI =	0.5
J-ring	
Diameter 1, in =	22.25
Diameter 2, in =	22.5
Average diameter, in =	22.4
T_{20}, sec =	1.73
L-box	
H1, in =	3.5
H2, in =	2.875
H2/H1 =	0.821428571
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.25 Fresh Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.38

Fresh concrete properties	
Mix ID	8/18/06-1
	3.38-A
Temperature	
Temperature, °F	80
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.12
Unit weight, lb/ft^3 =	138.5
Air content	
Air, % =	8.5
Slump	
Diameter 1, in =	21.75
Diameter 2, in =	21.75
Average diameter, in =	21.8
T_{20}, sec =	1.89
VSI =	0
J-ring	
Diameter 1, in =	21
Diameter 2, in =	19
Average diameter, in =	20.0
T_{20}, sec =	5.3
L-box	
H1, in =	4.5
H2, in =	2.0625
H2/H1 =	0.458333333
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.25 Fresh Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.38 (cont.)

Fresh concrete properties	
Mix ID	8/18/06-2
	3.38-B
Temperature	
Temperature, °F	79
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.34
Unit weight, lb/ft^3 =	139.4
Air content	
Air, % =	8.0
Slump	
Diameter 1, in =	21.5
Diameter 2, in =	22
Average diameter, in =	21.8
T_{20}, sec =	2.26
VSI =	0
J-ring	
Diameter 1, in =	20
Diameter 2, in =	19.25
Average diameter, in =	19.6
T_{20}, sec =	x
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	7.48
Coarse mass in bottom, g =	6.98
% difference, % =	-6.9

Table B.26 Fresh Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.42

Fresh concrete properties	
Mix ID	8/17/06-2
	3.42-C
Temperature	
Temperature, °F	85
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	42.18
Unit weight, lb/ft^3 =	138.8
Air content	
Air, % =	7.5
Slump	
Diameter 1, in =	24.5
Diameter 2, in =	24.5
Average diameter, in =	24.5
T_{20}, sec =	0.89
VSI =	0
J-ring	
Diameter 1, in =	22.5
Diameter 2, in =	22
Average diameter, in =	22.3
T_{20}, sec =	1.91
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	6
Coarse mass in bottom, g =	7.14
% difference, % =	17.4

Table B.26 Fresh Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.42 (cont.)

Fresh concrete properties	
Mix ID	8/17/06-3
	3.42-D
Temperature	
Temperature, °F	84
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	41.58
Unit weight, lb/ft^3 =	136.4
Air content	
Air, % =	8.5
Slump	
Diameter 1, in =	23
Diameter 2, in =	22
Average diameter, in =	22.5
T$_{20}$, sec =	1.04
VSI =	0
J-ring	
Diameter 1, in =	20.75
Diameter 2, in =	20.5
Average diameter, in =	20.6
T$_{20}$, sec =	3.88
L-box	
H1, in =	3.875
H2, in =	2.125
H2/H1 =	0.548387097
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.27 Fresh Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.46

Fresh concrete properties	
Mix ID	8/19/06-1
	3.46-A
Temperature	
Temperature, °F	75
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	41.94
Unit weight, lb/ft^3 =	137.8
Air content	
Air, % =	8.0
Slump	
Diameter 1, in =	23.5
Diameter 2, in =	23.75
Average diameter, in =	23.6
T_{20}, sec =	0.87
VSI =	0
J-ring	
Diameter 1, in =	23.25
Diameter 2, in =	23.125
Average diameter, in =	23.2
T_{20}, sec =	0.87
L-box	
H1, in =	
H2, in =	
H2/H1 =	
Column segregation	
Coarse mass in top, g =	6.42
Coarse mass in bottom, g =	6.94
% difference, % =	7.8

Table B.27 Fresh Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.46 (cont.)

Fresh concrete properties	
Mix ID	8/19/06-2
	3.46-B
Temperature	
Temperature, °F	76
Unit weight	
Measure only, lb =	7.76
Measure + concrete, lb =	41.66
Unit weight, lb/ft^3 =	136.7
Air content	
Air, % =	8.5
Slump	
Diameter 1, in =	24
Diameter 2, in =	23.25
Average diameter, in =	23.6
T_{20}, sec =	0.59
VSI =	0
J-ring	
Diameter 1, in =	21.25
Diameter 2, in =	22.25
Average diameter, in =	21.8
T_{20}, sec =	1.57
L-box	
H1, in =	3.875
H2, in =	2.375
H2/H1 =	0.612903226
Column segregation	
Coarse mass in top, g =	
Coarse mass in bottom, g =	
% difference, % =	

Table B.28 Hardened Concrete Tests for Rapid City Precast Mix, W/C = 0.38

Hardened concrete properties

Mix ID	7/13/06-2
	1.38-A

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/13/06-2-2	171,000	6048
		0
	Average =	6048

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/13/06-2-1	205500	7268
7/13/06-2-3	208000	7356
		0
		0
		0
		0
	Average =	7312

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/13/06-2-4	83000	734
		0
	Average =	734

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/13/06-2-1	12500	694
		0
	Average =	694

Table B.28 Hardened Concrete Tests for Rapid City Precast Mix, W/C = 0.38 (cont.)

Hardened concrete properties

Mix ID	7/14/06-1
	1.38-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/14/06-1-2	174,000	6154
7/14/06-1-7	173000	6119
	Average =	6136

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/14/06-1-1	204000	7215
7/14/06-1-3	215000	7604
7/14/06-1-5	201000	7109
		0
		0
		0
	Average =	7309

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/14/06-1-4	68000	601
7/14/06-1-8	64000	566
	Average =	601

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/14/06-1-1	13000	722
		0
	Average =	722

Table B.29 Hardened Concrete Tests for Rapid City Precast Mix, W/C = 0.42

Hardened concrete properties

Mix ID	7/12/06-1
	1.42-D

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/12/06-1-2	162,000	5730
7/12/06-1-6	152500	5394
	Average =	5562

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/12/06-1-1	207000	7321
7/12/06-1-7	195500	6914
7/12/06-1-5	198500	7021
		0
		0
		0
	Average =	7085

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/12/06-1-4	60000	531
		0
	Average =	531

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/12/06-1-1	13000	722
		0
	Average =	722

Table B.29 Hardened Concrete Tests for Rapid City Precast Mix, W/C = 0.42 (cont.)

Hardened concrete properties

Mix ID	7/13/06-1
	1.42-E

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/13/06-1-1	149,000	5270
7/13/06-1-4	158000	5588
	Average =	5429

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/13/06-1-3	182500	6455
		0
		0
		0
		0
		0
	Average =	6455

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/13/06-1-2	78000	690
		0
	Average =	690

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/13/06-1-1	12750	708
		0
	Average =	708

Table B.30 Hardened Concrete Tests for Rapid City Precast Mix, W/C = 0.46

Hardened concrete properties

Mix ID	7/17/06-1
	1.46-A

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/17/06-1-4	143,000	5058
		0
	Average =	5058

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/17/06-1-2	183500	6490
7/17/06-1-3	184500	6525
		0
		0
		0
		0
	Average =	6508

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/17/06-1-5	75000	663
		0
	Average =	663

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/17/06-1-1	13250	736
		0
	Average =	736

Table B.30 Hardened Concrete Tests for Rapid City Precast Mix, W/C = 0.46 (cont.)

Hardened concrete properties

Mix ID	7/17/06-2
	1.46-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/17/06-2-1	142,500	5040
7/17/06-2-4	153000	5411
	Average =	5226

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/17/06-2-2	189000	6685
7/17/06-2-7	191000	6755
7/17/06-2-8	187250	6623
		0
		0
		0
	Average =	6687

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/17/06-2-3	52250	462
7/17/06-2-6	63000	557
	Average =	510

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
		0
		0
	Average =	0

Table B.31 Hardened Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.38

Hardened concrete properties

Mix ID	7/25/06-1
	2.38-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/25/06-1-2	175,000	6189
7/25/06-1-6	189500	6702
	Average =	6446

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/25/06-1-5	219500	7763
7/25/06-1-7	230500	8152
		0
		0
		0
		0
	Average =	7958

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/25/06-1-1	67000	592
7/25/06-1-3	73250	648
	Average =	620

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/25/06-1-1	12500	694
		0
	Average =	694

Table B.31 Hardened Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.38 (cont.)

Hardened concrete properties

Mix ID	7/26/06-1
	2.38-C

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/26/06-1-4	186,000	6578
		0
	Average =	6578

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/26/06-1-1	215000	7604
7/26/06-1-3	200500	7091
		0
		0
		0
		0
	Average =	7348

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/26/06-1-2	70000	619
		0
	Average =	619

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/26/06-1-1	12150	675
		0
	Average =	675

Table B.32 Hardened Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.42

Hardened concrete properties

Mix ID	7/19/06-2
	2.42-A

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/19/06-2-4	143,500	5075
		0
	Average =	5075

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/19/06-2-1	175500	6207
7/19/06-2-3	178000	6295
		0
		0
		0
		0
	Average =	6251

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/19/06-2-2	55000	486
		0
	Average =	486

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/19/06-2-1	11125	618
		0
	Average =	618

Table B.32 Hardened Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.42 (cont.)

Hardened concrete properties

Mix ID	7/24/06-1
	2.42-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/24/06-1-2	141,000	4987
7/24/06-1-6	143000	5058
	Average =	5022

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/24/06-1-3	171500	6066
7/24/06-1-5	171500	6066
		0
		0
		0
		0
	Average =	6066

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/24/06-1-4	68500	606
		0
	Average =	606

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/24/06-1-1	11150	619
		0
	Average =	619

Table B.33 Hardened Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.46

Hardened concrete properties

Mix ID	7/18/06-1 2.46-A

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/18/06-1-1	139,000	4916
7/18/06-1-4	134000	4739
	Average =	4828

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/18/06-1-2	169500	5995
7/18/06-1-3	169000	5977
		0
		0
		0
		0
	Average =	5986

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/18/06-1-5	55000	486
		0
	Average =	486

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
		0
		0
	Average =	0

Table B.33 Hardened Concrete Tests for Rapid City Cast-In-Place Mix, W/C = 0.46 (cont.)

Hardened concrete properties

Mix ID	7/19/06-1 2.46-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
7/19/06-1-6	138,500	4898
		0
	Average =	4898

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
7/19/06-1-1	175000	6189
7//19/06-1-3		0
		0
		0
		0
		0
	Average =	6189

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
7/19/06-1-2	59500	526
7//19/06-1-4	53000	469
	Average =	526

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
7/19/06-1-1	10500	583
7/19/06-1-2	12125	674
	Average =	583

Table B.34 Hardened Concrete Tests for Mitchell Precast Mix, W/C = 0.38

Hardened concrete properties

Mix ID	8/21/06-3
	4.38-A

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/21/06-3-5	147,000	5199
8/21/06-3-6	159500	5641
	Average =	5420

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/21/06-3-3	206000	7286
8/21/06-3-4	201000	7109
	Average =	7197

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/21/06-3-1	73500	650
	Average =	650

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/21/06-3-1	11600	644
	Average =	644

Table B.34 Hardened Concrete Tests for Mitchell Precast Mix, W/C = 0.38 (cont.)

Hardened concrete properties

Mix ID	8/22/06-1
	4.38-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/22/06-1-2	161,500	5712
8/22/06-1-4	147500	5217
	Average =	5464

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/22/06-1-1	203000	7180
8/22/06-1-3	195000	6897
	Average =	7038

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/22/06-1-4	67500	597
	Average =	597

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/22/06-1-1	11850	658
	Average =	658

Table B.35 Hardened Concrete Tests for Mitchell Precast Mix, W/C = 0.42

Hardened concrete properties

Mix ID	8/21/06-2 4.42-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/21/06-2-1	156,000	5517
8/21/06-2-2	157000	5553
	Average =	5535

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/21/06-2-3	187000	6614
8/21/06-2-4	196000	6932
	Average =	6773

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/21/06-2-6	69500	615
8/21/06-2-7	61500	544
	Average =	579

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/21/06-2-1	9900	550
	Average =	550

Table B.35 Hardened Concrete Tests for Mitchell Precast Mix, W/C = 0.42 (cont.)

Hardened concrete properties

Mix ID	8/23/06-1
	4.42-C

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/23/06-1-4	147,500	5217
	Average =	5217

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/23/06-1-1	180000	6366
8/23/06-1-3	178500	6313
	Average =	6340

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/23/06-1-2	67500	597
	Average =	597

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/23/06-1-1	10000	556
	Average =	556

Table B.36 Hardened Concrete Tests for Mitchell Precast Mix, W/C = 0.46

Hardened concrete properties

Mix ID 8/22/06-2
4.46-A

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/22/06-2-3	147,000	5199
	Average =	5199

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/22/06-2-2	183000	6472
8/22/06-2-4	189000	6685
	Average =	6578

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/22/06-2-1	48500	429
	Average =	429

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/22/06-2-1	9900	550
	Average =	550

Table B.36 Hardened Concrete Tests for Mitchell Precast Mix, W/C = 0.46 (cont.)

Hardened concrete properties

Mix ID	8/22/06-3
	4.46-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/22/06-3-1	136,000	4810
8/22/06-3-2	145000	5128
	Average =	4969

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/22/06-3-3	187000	6614
8/22/06-3-4	185500	6561
	Average =	6587

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/22/06-3-5	62500	553
8/22/06-3-7	63000	557
	Average =	555

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/22/06-3-1	9700	539
	Average =	539

Table B.37 Hardened Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.38

Hardened concrete properties

Mix ID	8/18/06-1 3.38-A

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/18/06-1-4	163,000	5765
8/18/06-1-5	164000	5800
	Average =	5783

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/18/06-1-2	191000	6755
8/18/06-1-3	216000	7639
	Average =	7197

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/18/06-1-6	71000	628
8/18/06-1-7	67500	597
	Average =	612

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/18/06-1-1	10500	583
	Average =	583

Table B.37 Hardened Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.38 (cont.)

Hardened concrete properties

Mix ID	8/18/06-2
	3.38-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/18/06-2-2	174,500	6172

Average = 6172

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/18/06-2-4	208500	7374
8/18/06-2-?	215000	7604

Average = 7489

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/18/06-2-1	71000	628

Average = 628

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/18/06-2-1	10800	600

Average = 600

Table B.38 Hardened Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.42

Hardened concrete properties

Mix ID	8/17/06-2
	3.42-C

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/17/06-2-5	157,000	5553
	Average =	5553

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/17/06-2-1	180500	6384
8/17/06-2-4	189000	6685
	Average =	6534

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/17/06-2-3	64000	566
	Average =	566

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/17/06-2-1	10700	594
	Average =	594

Table B.38 Hardened Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.42 (cont.)

Hardened concrete properties

Mix ID	8/17/06-3
	3.42-D

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/17/06-3-1	149,500	5287
8/17/06-3-7	156500	5535
	Average =	5411

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/17/06-3-2	180000	6366
8/17/06-3-3	181000	6402
8/17/06-3-6	194000	6861
	Average =	6543

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/17/06-3-5	61500	544
8/17/06-3-8	64000	566
	Average =	555

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/17/06-3-1	9700	539
	Average =	539

Table B.39 Hardened Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.46

Hardened concrete properties

Mix ID	8/19/06-1
	3.46-A

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/19/06-1-1	130,000	4598
	Average =	4598

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/19/06-1-2	166500	5889
8/19/06-1-4	170000	6013
	Average =	5951

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/19/06-1-3	57500	508
	Average =	508

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/19/061-1	9700	539
	Average =	539

Table B.39 Hardened Concrete Tests for Mitchell Cast-In-Place Mix, W/C = 0.46 (cont.)

Hardened concrete properties

Mix ID	8/19/06-2
	3.46-B

Compressive strength 7 days

Cylinder ID	Load, lb	Strength, psi
8/19/06-2-6	128,000	4527
8/19/06-2-7	129500	4580
	Average =	4554

Compressive strength 28 days

Cylinder ID	Load, lb	Strength, psi
8/19/06-2-2	161500	5712
8/19/06-2-4	170000	6013
8/19/06-2-8	162500	5747
	Average =	5824

Split cylinder

Cylinder ID	Load, lb	Tensile strength, psi
8/19/06-2-2	49500	438
8/19/06-2-5	58000	513
	Average =	475

Beam with three point loading

Beam ID	Load, lb	Modulus of rupture, psi
8/19/06-2-1	9800	544
	Average =	544

APPENDIX C: SPECIAL PROVISIONS

STATE OF SOUTH DAKOTA
DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION
FOR
SELF-CONSOLIDATING CONCRETE (SCC)
FOR PRECAST BOX CULVERTS

PROJECT NUMBER, PCN NUMBER
NAME COUNTY

APRIL 25, 2007

I DESCRIPTION

This work consists of furnishing and installing precast self-consolidating concrete (SCC) box culvert items.

II MATERIALS

A. Concrete:

1. **Fine Aggregate:** Section 800.

2. **Coarse Aggregate:** Coarse aggregate for SCC shall meet the requirements of Section 820 with the following exceptions:

Coarse aggregate used in SCC shall be either quartzite or limestone aggregate conforming to the following gradation requirements:

	Percent Passing	
Sieve Size	**Quartzite**	**Limestone**
5/8 inch (16.0 mm)	100	
1/2 inch (12.5 mm)	90 to 100	100
3/8 inch (9.50 mm)	70 to 90	90 to 100
No. 4 (4.75 mm)	0 to 30	0 to 20
No. 8 (2.36 mm)	0 to 15*	0 to 5*

* The combined mixture of fine and coarse aggregate shall be such that not more than 1.5 percent passes the No. 200 (75 μm) sieve.

The maximum amount of flat and elongated particles for the coarse aggregate shall not exceed 25% when tested according to ASTM D 4791-99. Flat and elongated particles are defined as those particles having a ratio of maximum to minimum dimension greater than three to one. The aggregate tested shall be the material retained on a No. 4 (4.75 mm) sieve and larger.

The percent of flat and elongated particles for the coarse aggregate shall be tested at the same frequency as the coarse aggregate gradation.

3. **Water:** Section 790.

4. **Admixtures:** Section 751 and 752. The Contractor may use viscosity modifying admixtures (VMA) to attain the desired SCC performance. VMA for use in SCC must be submitted to the Concrete Engineer for approval with the mix design.

5. **Cement:** Section 750. Type I/II Portland Cement shall be used for all SCC. No substitutions will be allowed.

B. **Reinforcing Steel:** Section 1010.

C. **Drainage Fabric:** Section 831.1 – Type A.

III CONSTRUCTION REQUIREMENTS

A. **General Requirements: The Contractor shall satisfy the following for all precast SCC items.**

1. **Concrete Mix Requirements:** The Contractor shall submit a concrete job mix design for approval ten working days prior to fabrication. The mix design shall include all aggregate sources and admixtures proposed for use.

   a. **Minimum Cement Content:** The SCC shall contain a minimum cement content of 700 pound per cubic yard (415 Kilograms per cubic meter).

   b. **Maximum Water Cement Ratio:** The mix design shall establish a maximum water cement ratio for all SCC produced. This maximum water cement ratio shall never exceed 0.46.

   c. **Minimum Coarse Aggregate Content:** The SCC shall consist of a minimum coarse aggregate content of 40 percent of the total aggregate content by weight.

   d. **Entrained Air Content Range:** The SCC shall contain an entrained air content of between 4.5 and 7.5 percent. The procedure for testing of entrained air content shall be performed as described in SD 403 with the following exceptions:

   The air content meter bucket shall be filled in one continuous lift. Rodding of the concrete shall not be permitted. Light tamping by hand on the side of the bucket may be allowed to remove cavities and large air bubbles.

e. **Slump Flow at Time of Placement:** The slump flow at time of placement for SCC shall be between twenty-two and twenty-eight inches (22” - 28”) when tested according to ASTM C 1611/C 1611M - 05, filling procedure B (inverted mold).

f. **Visual Stability Index (VSI) at Time of Placement:** The VSI of the SCC at the time of placement shall not exceed 1 when tested according to ASTM C 1611/C 1611M – 05.

g. **Difference between J-Ring Spread and Slump Flow Spread:** The difference between the J-Ring spread and the slump flow spread shall not be greater than 2.0 inches. The J-Ring spread shall be tested according to ASTM C 1621/C 1621M – 06. The slump flow spread shall be tested according to ASTM C 1611/C 1611M – 05, filling procedure B (inverted mold).

h. **Minimum 28 Day Compressive Strength:** The SCC shall obtain a minimum 28 day compressive strength equal to or greater than the minimum compressive strength specified. The procedure for filling molds and beams shall be performed as described in SD 405 with the following exceptions:

The concrete cylinder molds shall be filled in one continuous lift. Rodding of the concrete shall not be permitted. Light tamping by hand on the side of the mold may be allowed to remove cavities and large air bubbles.

The absolute volume of mix proportions shall yield 27.0 to 27.25 cubic feet.

All mix designs and any modifications thereto, including changes in admixtures, shall be submitted with the mix design. The Mix design data and test results shall be recorded on a DOT Form 24 and submitted to the Engineer.

Equipment and methods used for batching, mixing, and transporting of the concrete shall be approved by the Engineer.

2. **Shop Drawings:** Fifteen days prior to fabrication, the Contractor shall furnish shop drawings for Department review. The shop drawings shall consist of fabrication details including reinforcing steel and spacer placement and configurations, total quantities for the complete structure, and all information necessary for fabrication and erection.

3. **Forms:** The forms shall be designed to withstand the fluid pressure of the concrete and the added forces due to vibration and impact without distortion. The forms shall be mortar tight and free from warp.

The form area in contact with the concrete shall be treated with an approved form oil or wax before the form is set in position. The forms shall be thoroughly cleaned of all other substances.

4. **Concrete Cure:** The concrete shall be cured by low pressure steam, radiant heat, or as specified in Section 460.3 N. When curing in accordance with Section 460.3 N, the concrete temperature requirements of Section 460.3 O shall apply.

Low pressure steam or radiant heat curing shall be done under an enclosure to contain the live steam or the heat and prevent heat and moisture loss. The concrete shall be allowed to attain initial set before application of the steam or heat. The initial application of the steam or heat shall be three hours after the final placement of concrete to allow the initial set to occur. When retarders are used, the waiting period before application of the steam or radiant heat shall be five hours. When the time of initial set is determined by ASTM C 403, the time limits described above may be waived.

During the waiting period, the minimum temperature within the curing chamber shall not be less than 50° F (10° C) and live steam or radiant heat may be used to maintain the curing chamber between 50° F (10° C) and 80° F (27° C). During the waiting period the concrete shall be kept moist.

Application of live steam shall not be directed on the concrete forms causing localized high temperatures. Radiant heat may be applied by pipes circulating steam, hot oil, hot water, or by electric heating elements. Moisture loss shall be minimized by covering exposed concrete surfaces with plastic sheeting or by applying an approved liquid membrane curing compound to exposed concrete surfaces. The top surface of concrete members for use in composite construction shall be free of membrane curing compound residue unless suitable mechanical means for full bond development are provided.

During the initial application of live steam or radiant heat, the concrete temperature shall increase at an average rate not exceeding 40° F (22° C) per hour until the curing temperature is reached. The maximum concrete temperature shall not exceed 160° F (71° C). The maximum temperature shall be held until the concrete has reached the desired strength. After discontinuing the steam or radiant heat application, the temperature of the concrete shall decrease at a rate not to exceed 40° F (22° C) per hour until the concrete temperature is within 20° F (11° C) of the ambient air temperature. The Contractor will not be required to monitor this cool down temperature when the ambient air temperature is 20° F (11° C) or above.

The test cylinders shall be cured with the unit, or in a similar manner (similar curing method and concrete curing temperature, as approved by the Concrete Engineer) as the unit, until minimum compressive strength has been obtained

5. **Surface Finish and Patching:** If a precast item shows stone pockets, honeycomb, delamination or other defects which may be detrimental to the structural capacity of the item, it will be subject to rejection at the discretion of the Engineer. Minor surface irregularities or cavities, which do not impair the service of the item, and which are satisfactorily repaired will not constitute cause for rejection. Repairs shall not be made until the Engineer has inspected the extent of the irregularities and has determined whether the item can be satisfactorily repaired. If the item is deemed to be repairable, the repair method and procedures shall be agreed upon by the Department and fabricator prior to the work commencing.

   Depressions resulting from the removal of metal ties or other causes shall be carefully pointed with a mortar of sand and cement in the proportions, which are similar to the specific class of concrete in the unit. A sack rub finish is required on sloped surfaces of box culvert end sections.

B. Precast Box Culverts: The following shall apply to box culverts:

1. **Design:** Precast concrete box culverts shall conform to AASHTO M 259 or M 273. Configurations in variance with those provided by AASHTO will be accepted provided the AASHTO materials, design, fabrication specification and the requirements of this Section are complied with.

   Box culvert end sections (inlet or outlet) materials, design, and fabrication shall conform to AASHTO Standard Specifications for Highway Bridges and Materials Specifications.

   Precast box culverts shall be designed to specified load conditions. The Design Engineer of the structure must be registered in the State of South Dakota. The design shall conform to the AASHTO design requirements for the depth of fill, including surfacing, etc., as well as live load or specified loading. The specified live load shall apply to all barrel sections.

   Minimum reinforcing steel clear cover shall be 1 inch (25mm) for all member faces. The exception to this is that box culverts covered by a fill of less than 2 feet (0.6 m) shall have a minimum reinforcing steel clear cover of 2 inches (50 mm) in the top of the top slab.

   The Contractor shall furnish a checked design with the shop drawings. A checked design includes the design calculations, and check design calculations performed by an independent Engineer.

   A checked design for barrel sections will not be required to be submitted if the proposed fabrication dimensions and reinforcement conform to AASHTO M 259M or M 273M. A checked design for the end sections and special sections will be required.

2. **Fabrication:** The Contractor shall notify the Engineer seven days prior to fabrication.

   The minimum length of precast section shall be four feet. (1200 mm)

   Welding of reinforcing steel will not be permitted.

   Joint ties shall be provided on all sections.

   Steel wire bar supports shall be used to maintain proper reinforcement location and concrete cover. Cutting of reinforcement and bending to the form surface, for support, will not be permitted. Steel wire bar supports, in contact with the casting forms, shall be stainless steel, hot dipped galvanized, or plastic tipped extending at least ½ inch (13 mm) from the form surface.

   The surface temperature of forms and reinforcing steel (that come in contact with the concrete being placed) shall be raised to a temperature above freezing prior to concrete placement. All deleterious material shall be removed from the forms prior to concrete placement.

The Contractor shall not vibrate the SCC. Limited vibrating may be allowed, when necessary, as approved by the Engineer.

The precast units shall have sufficient strength to prevent damage to the units during removal of the forms and yarding. Precast units shall have a minimum concrete compressive strength of 800 psi (5.5 MPa) prior to form removal. Precast units shall have a minimum concrete compressive strength of 3000 psi (21 MPa) prior to yarding. The Engineer may approve a different minimum concrete strength for form removal and yarding, based upon fabricator demonstrated results or as shown on design details submitted and approved with the shop plans.

3. **Testing:** Sampling and testing by the Department shall be in accordance with the Materials Manual with the following exceptions:

   a. **Fresh (plastic) concrete tests:** The fresh (plastic) concrete tests shall be performed a minimum of twice per precast unit except that strength tests will be required at a frequency of one test per precast unit.

   b. **Slump Flow Spread:** Slump flow spread shall be tested each time a fresh concrete test is performed.

   c. **J-Ring Spread:** J-Ring spread shall be tested at a rate of one out of every two fresh concrete tests.

      When the slump flow spread and the J-Ring spread tests are both performed, the tests shall be performed concurrently or subsequently with no more than two minutes elapsed time between the slump flow spread and J-ring spread tests.

   d. **Entrained Air Content:** Entrained air content shall be tested at a rate of one out of every two fresh concrete tests.

   e. **Unit Weight:** Unit weight shall be tested with each entrained air content test.

   f. **Temperature:** Temperature shall be tested with each entrained air content test.

   g. **Concrete Compressive Strength:** The Department shall make a minimum of one group of test cylinders for each class of concrete for each day's production, not to exceed 150 cubic yards (125 cubic meters) per group of cylinders.

      At a minimum, a group of test cylinders shall consist of the following:

      1) Two test cylinders are required for the 28 day compression test.

      2) Three additional cylinders will be required for determining concrete strength for tipout, 7, & 14 day.

Acceptance of the precast units shall be in accordance with Section 460.3 B. The precast units will be accepted when the minimum design concrete compressive strength requirements have been met.

4. **Installation:** Box culvert installation shall conform to the approved shop drawings and the following:

   a. **Foundation:** Foundation preparation shall be in accordance with Sections 420, 421, and 450. The foundation shall be shaped to provide a satisfactory template section and density.

   b. **Transverse Joints:** The floor joint between adjacent sections shall be sealed with a preformed mastic along the floor to the top of the haunches. Fabric shall be placed along the top and walls, to provide a minimum of 2 ½ feet (750 mm) of fabric centered on the joint. Transverse joints in the fabric shall be overlapped at least two feet (600 mm). Sufficient adhesive shall be required along the edge of the fabric to hold it in place while backfilling. The lift holes shall be plugged with an approved non-shrink grout or as shown on the approved shop drawings.

      The maximum allowable gap at any point between adjacent sections of box culvert shall be 1” (25 mm).

   c. **Joint Ties:** Each section shall be tied to adjacent sections with joint ties as shown on the approved shop drawings.

   d. **Backfilling:** Backfilling shall conform to Section 450. Hand compaction methods may be required for satisfactory compaction under and adjacent to corners with radius and between culverts on multiple installations.

IV METHOD OF MEASUREMENT

A. **Furnishing Precast Box Culvert:** Measurement for furnishing precast box culverts will not be made. Plans quantity shall be used for payment.

B. **Installing Precast Box Culvert:** Measurement for installing precast box culvert will not be made. Plans quantity shall be used for payment

C. **Furnishing Precast Box Culvert End Sections:** Furnishing precast box culvert end sections will be measured per each. One end section will be considered to be all of the individual pieces required to construct one end of the box culvert.

D. **Installing Precast Box Culvert End Sections:** Installing precast box culvert end sections will be measured per each. One end section will be considered to be all of the individual pieces required to construct one end of the box culvert.

V BASIS OF PAYMENT

A. **Furnishing Precast Box Culvert:** Furnish precast box culvert will be paid for at the contract unit price per 0.1 foot (0.1 meter). Payment will be full compensation for furnishing the box culvert, joint seal mastic, drainage fabric, and joint ties.

B. **Installing Precast Box Culvert:** Installing precast box culvert will be paid for at the contract unit price per 0.1 foot (0.1 meter). Payment will be full compensation for precast box culvert installation and will include compensation for foundation preparation, backfilling, and all other incidentals.

C. **Furnishing Precast Box Culvert End Sections:** Furnishing precast box culverts will be paid for at the contract unit price per each.

D. **Installing Precast Box Culvert End Sections:** Installing precast box culvert end sections will be paid for at the contract unit price per each.

* * * * *

STATE OF SOUTH DAKOTA
DEPARTMENT OF TRANSPORTATION

SPECIAL PROVISION
FOR
SELF-CONSOLIDATING CONCRETE FOR BOX CULVERTS

PROJECT NUMBER, PCN NUMBER
NAME COUNTY

MARCH 7, 2008

Modify Section 460 of the Standard Specifications for Roads and Bridges as follows. These modifications apply only to concrete produced under the bid item for Class A45 Concrete, Self Consolidating. These modifications to Section 460 of the Standard Specification for Roads and Bridges do not apply to any other structural concrete.

Delete Section 460.1 and replace with the following:

460.1 DESCRIPTION

This work consists of falsework and form construction, and the furnishing, handling, placing, curing, and finishing of self-consolidating concrete (SCC) for box culverts. The SCC shall be Class A45 Concrete, Self Consolidating.

Delete Section 460.2 and replace with the following:

460.2 MATERIALS

Materials shall conform to the following Sections:

A. **Cement:** Section 750. Type I/II Portland Cement shall be used for all SCC. No substitutions will be allowed.

B. **Fine Aggregate:** Section 800.

C. **Coarse Aggregate:** Coarse aggregate for SCC shall meet the requirements of Section 820 with the following exceptions:

Coarse aggregate used in SCC shall be either quartzite or limestone aggregate conforming to the following gradation requirements:

Sieve Size	**Percent Passing**
1 inch (25.0 mm)	100
3/4 inch (19.0 mm)	90 to 100
3/8 inch (9.50 mm)	30 to 100
No. 4 (4.75 mm)	0 to 30
No. 8 (2.36 mm)	0 to 15*

* The combined mixture of fine and coarse aggregate shall be such that not more than 1.5 percent passes the No. 200 (75 μm) sieve.

The maximum amount of flat and elongated particles for the coarse aggregate shall not exceed 30% when tested according to ASTM D 4791-99. Flat and elongated particles are defined as those particles having a ratio of maximum to minimum dimension greater than three to one. The aggregate tested shall be the material retained on a No. 4 (4.75 mm) sieve and larger.

The percent of flat and elongated particles for the coarse aggregate shall be tested at the same frequency as the coarse aggregate gradation.

D. **Water:** Section 790.

E. **Admixtures:** Sections 751 and 752. The Contractor may use viscosity modifying admixtures (VMA) to attain the desired SCC performance. VMA for use in SCC must be submitted to the Concrete Engineer for approval with the mix design.

F. **Reinforcing Steel:** Section 1010.

G. **Curing Materials:** Section 821.

H. **Fly Ash:** Section 753.

Delete Section 460.3 A and replace with the following:

A. **Concrete Quality and Proportion:** The Contractor shall design and be responsible for the performance of all concrete mixes used in structures. The mix proportions shall produce SCC that is sufficiently workable and finishable for all uses intended and shall conform to the following requirements:

1. **Minimum Cement Content:** The SCC shall contain a minimum cement content of 700 pound per cubic yard (415 Kilograms per cubic meter).

2. **Maximum Cementitious Content:** The maximum cementitious content (total cement, fly ash, and other cementitious admixture) content shall be 800 pounds per cubic yard (475 Kilograms per cubic meter).

3. **Maximum Water Cement Ratio:** The mix design shall establish a maximum water cement ratio for all SCC produced. This maximum water cement ratio shall never exceed 0.46.

4. **Minimum Coarse Aggregate Content:** The SCC shall consist of a minimum coarse aggregate content of 45 percent.

5. **Entrained Air Content Range:** The SCC shall contain an entrained air content of between 5 and 7.5 percent. The procedure for testing of entrained air content shall be performed as described in SD 403 with the following exceptions:

   The air content meter bucket shall be filled in one continuous lift. Rodding of the concrete shall not be permitted. Light tamping by hand or rubber mallet on the side of the bucket may be allowed to remove cavities and large air bubbles.

6. **Slump Flow at Time of Placement:** The slump flow at time of placement for SCC shall be between twenty-two and twenty-eight inches (22” - 28”) when tested according to ASTM C 1611/C 1611M - 05, filling procedure B (inverted mold).

7. **Visual Stability Index (VSI) at Time of Placement:** The VSI of the SCC at the time of placement shall not exceed 1 when tested according to ASTM C 1611/C 1611M – 05.

8. **Difference between J-Ring Spread and Slump Flow Spread:** The difference between the J-Ring spread and the slump flow spread shall not be greater than 2.0 inches. The J-Ring spread shall be tested according to ASTM C 1621/C 1621M – 06. The slump flow spread shall be tested according to ASTM C 1611/C 1611M – 05, filling procedure B (inverted mold).

9. **Minimum 28 Day Compressive Strength:** The SCC shall obtain a minimum 28 day compressive strength of 4500 psi (31 MPa). The procedure for filling molds and beams shall be performed as described in SD 405 with the following exceptions:

   The concrete cylinder molds shall be filled in one continuous lift. Rodding of the concrete shall not be permitted. Light tamping by hand or rubber mallet on the side of the mold may be allowed to remove cavities and large air bubbles.

10. **Admixtures:** VMA and polycarboxilate, if added, shall be added to the SCC at the location of placement or at an alternate location approved by the Engineer.

The absolute volume of mix proportions shall yield 27.0 to 27.25 cubic feet.

The mix design shall be based upon obtaining an average concrete compressive strength 1,200 psi above the specified minimum 28 day compressive strength.

Satisfactory performance of the proposed mix design shall be verified by laboratory tests on trial batches. Trial batches shall be conducted in accordance with the American Concrete Institute Publication ACI 211.1, ACI 318, and ASTM C 192 except that the air content shall be within 0.5% ± of the maximum specified.

The results of such tests shall be furnished by the Contractor to the Engineer at the time the proposed mix design is submitted.

Concrete mix design previously used in other work will be considered in compliance with the mix design requirements provided all of the following conditions are met:

> The concrete mix proportions should be in accordance with this provision.
>
> The mix design including all materials, gradations, and admixtures are identical to those previously used and tested.
>
> The average 28 day compressive strength of 10 or more test results from an approved testing facility is at least 1.34 standard deviations above the specified strength. These strength test results shall be submitted to the Engineer, with

companion batch tickets, air content, slump flow, VSI, and J-Ring test results. No strength test results may be below the minimum specified strength.

All mix designs and any modifications thereto, including changes in admixtures, shall be submitted for approval. Mix design data and test results shall be recorded on a DOT Form 24 and submitted to the Engineer.

Delete Section 460.3 C.3 and replace with the following:

3. **Formwork:** Formwork shall be complete and joints made mortar tight. Concrete formwork shall be in accordance with Section 423 Temporary Works. Because of the casting properties of SCC, concrete forms shall be rigid enough to maintain dimensional tolerances and withstand form pressure that is developed by the concrete in its plastic state. Formwork shall be designed for full fluid pressure. The form joints shall be sealed sufficiently to prevent the mortar leakage that could occur with SCC.

Delete Section 460.3 H and replace with the following:

H. **Delivery Requirements:** SCC must be continuously agitated in the hauling unit, SCC shall be discharged within 90 minutes, and discharged and screeded within 105 minutes after the cement has been placed in contact with the aggregates.

The rate of delivery shall be uniform. The interval between batches shall not exceed 30 minutes.

The Contractor may be allowed to use a set retarding admixture to control initial set when approved by the Engineer. When set retarding admixtures are allowed, the concrete delivery requirements may be adjusted. The Contractor shall submit proposed delivery requirement changes to the Concrete Engineer for approval.

The contractor, using the manufacturer’s recommendations, shall establish the amount of admixtures that may be added in the field when approved by the Engineer.

If, after additional admixture adjustments in the field, the concrete does not conform to the quality requirements of Section 460.3 A the concrete shall be considered for rejection.

Delete Section 460.3 K and replace with the following:

K. **Placing Concrete:** The Contactor shall give sufficient notice before starting to place concrete to permit inspection of forms, reinforcing steel, and preparation for placing. Concrete shall not be placed without approval of the Engineer.

Placement of concrete on a frozen foundation will not be permitted. The surface temperature of forms, steel, and adjacent concrete which will come in contact with the concrete being placed shall be raised to a temperature above freezing prior to placement.

The temperature of concrete immediately after placing shall be no less than 50º F (10º C) and no more than 85º F (29º C).

Before placing concrete, sawdust, chips, debris, and extraneous matter shall be removed from the interior of forms. Temporary struts, stays, and braces holding the forms in the correct shape and alignment, shall be removed when the fresh concrete has reached an elevation rendering their service unnecessary. These temporary members shall not be buried in the concrete.

The slope of chutes for concrete placement shall allow the concrete to flow slowly without segregation. Chutes and spouts shall be kept clean and shall be thoroughly flushed with water before and after each run. The flush water shall be discharged outside the forms.

Free fall of concrete shall not exceed 5 feet (1.5 meters). In thin walls or columns where the reinforcement prohibits the use of chutes the method of placement shall not lead to segregation of the concrete. The use of drop tubes or tremies is encouraged to limit concrete drop heights, to keep reinforcement clean, and to limit segregation. When a concrete pump is utilized, free fall of concrete shall not exceed 1 foot (.3 meters). Horizontal flow distance shall not exceed 30 feet (9 meters).

The sequence of placing concrete, including the location of construction joints, shall be as specified. Concrete shall be placed in continuous horizontal layers. Each layer shall be placed before the preceding layer has attained its initial set.

The Contractor shall not vibrate the SCC. Limited vibrating may be allowed, when necessary, as approved by the Engineer.

Accumulations of mortar splashed upon the reinforcing steel and the surfaces of forms shall be satisfactorily removed. Care shall be exercised not to injure or break the concrete to steel bond at and near the surface of the concrete while cleaning the reinforcing steel. Dried mortar chips and dust shall be removed and not left in the unset concrete.

Add the following to Section 460.3:

T. **Frequency of Testing:** Sampling and testing by the Department shall be in accordance with the Materials Manual with the following exceptions:

1. **First Three Truckloads:** The fresh (plastic) concrete tests listed in Section 460.3 T.2 shall be performed on the concrete from the first three truckloads of any individual concrete placement. Sampling of the concrete for this application shall be at the beginning of the batch after 5 gallons of concrete has been discharged from the mixing drum. This material shall be wasted and not included in the finish product. The slump flow spread and the J-Ring spread tests shall be performed concurrently or subsequently with no more than two minutes elapsed time between the slump flow spread and the J-Ring spread tests. Samples of concrete for entrained air content shall be obtained from the discharge end of the pump in accordance with the Materials Manual.

2. **Subsequent Truckloads:** After the first three truckloads, fresh (plastic) concrete tests shall be performed on the concrete from all subsequent truckloads at the following frequency:

a. **Slump Flow Spread:** Slump flow spread shall be tested at a rate of every conveyance.

b. **J-Ring Spread:** J-Ring spread shall be tested at a rate of one out of every two conveyances.

   The slump flow spread and the J-Ring spread tests shall be performed on the same conveyance. The slump flow spread and the J-Ring spread tests shall be performed concurrently or subsequently with no more than two minutes elapsed time between the slump flow spread and J-ring spread tests.

c. **Entrained Air Content:** Entrained air content shall be tested at a rate of one out of every four conveyances.

d. **Unit Weight:** Unit weight shall be tested at a rate of one out of every four conveyances.

e. **Temperature:** Temperature shall be tested at a rate of every conveyance.

Delete Section 460.4 and replace with the following:

460.4 METHOD OF MEASUREMENT

SCC will be measured in accordance with the neat line dimensions shown on the plans to the nearest 0.1 cubic yard (0.1 cubic meter), unless changes are ordered in writing.

Deductions will not be made for the volume of concrete occupied by utility conduit, six inch (150 mm) or smaller drainage pipe, reinforcing steel, encased structural steel, pile heads, anchors, sleeves and encased grillage, or for volume of concrete displaced by weep holes, joints, drains and scuppers or for fillets, chamfers or scorings, one inch square (10 square centimeters) or less in cross section.

Commercial texture finish will not be measured for payment.

Delete Section 460.5 and replace with the following:

460.5 BASIS OF PAYMENT

The accepted quantities of SCC will be paid for at the contract unit price per cubic yard (cubic meter).

Payment will be full compensation for labor, equipment, tools, materials and all other items of work required in furnishing, forming, placing, finishing, curing, protecting and all other items incidental to the SCC.

Reinforcing and structural steel will be paid for separately.

When a bid item for concrete is provided, it will be considered full compensation for excavation necessary to construct the structure, unless a separate item is provided for such excavation.

Commercial texture finish will be incidental to the unit bid price for structural concrete.

Delete the first paragraph of Section 480.3 C and replace with the following:

C. **Placing and Fastening:** Reinforcing steel shall be accurately placed and firmly held in the positions specified using steel chairs or other approved methods. Bars shall be tied at all intersections.

* * * * *

APPENDIX D: ADMIXTURE LITERATURE

Concrete

PRODUCT INFORMATION

ADVA® Cast 555

Superplasticizer for Precast Concrete ASTM C494, Type F

Description

ADVA® Cast 555 is a high efficiency polycarboxylate based superplasticizer. ADVA Cast 555 has been formulated to impart maximum desired workability without segregation to concrete, and to achieve high early compressive strength as required by the precast industry. ADVA Cast 555 is optimized for the production of Self-Consolidating Concrete (SCC) in precast/ prestressed applications.

ADVA Cast 555 is formulated to comply with ASTM C494 as a Type F admixture and meets the provisional requirements. One year ASTM will be complete in June 2006.

Uses

ADVA Cast 555 is recommended for use in precast and prestressed production in Self-Consolidating Concrete and conventional applications.

Self-Consolidating Concrete Applications:

Self-Consolidating Concrete produced with ADVA Cast 555 has unique advantages over conventional flowing concrete.

- Lower SCC Viscosity: flow properties of SCC are enhanced, reducing SCC viscosity with no change in stability or segregation resistance.
- Self Placement: vibration can be eliminated because SCC is highly flowable and will change shape under its own weight to self level and self consolidate within formwork.
- High Cohesion: the window of acceptable mix designs to maintain cohesive SCC's is increased, allowing for the production of SCC that is flowable and yet highly cohesive. Bleeding is significantly reduced.
- No Blocking: SCC can pass freely through narrow openings and congested reinforcement without aggregate "blocking" behind obstructions that stop the flow of concrete.

GRACE
Construction Products

Self-Consolidating Concrete produced with ADVA Cast 555 provides the following benefits:

- Reduced labor and improved productivity through faster and easier concrete placement with no vibration
- The highest quality surface finish, eliminating/reducing the need for surface touch ups
- Improved labor safety, reduced plant noise levels and improved work environment
- Reduced wear and tear on forms by eliminating vibration
- Achievement of complete consolidation throughout concrete elements, even in thin walled, highly reinforced units
- Increased production flexibility by enabling use of form geometry and form orientations in which placement of conventional concrete mixes would be difficult or impossible

Conventional Concrete Applications:

- ADVA Cast 555 superplasticizer can produce concrete with extremely high levels of workability without segregation.
- ADVA Cast 555 may be used to produce concrete with very low water/cement ratios while maintaining normal levels of workability.
- ADVA Cast 555 is ideal for use in precast and prestressed applications where concrete needs to achieve high early strength along with high levels of workability.
- ADVA Cast 555 provides superior concrete surface finish characteristics with reduced bugholing.

Dosage Rates

ADVA Cast 555 is an easy to dispense liquid admixture. Dosage rates can be adjusted to meet a wide spectrum of concrete performance requirements. Addition rates for ADVA Cast 555 can vary with the type of application, but will normally range from 540 to 1400 mL/100 kg (8 to 20 fl oz/100 lbs) of cement. Should conditions require using more than the recommended addition rate, please consult your Grace Representative.

For Self-Consolidating Concrete applications, pre-placement testing is recommended to determine the optimum admixture addition rate and mix design. Factors that influence optimum addition rate include other concrete mix components, aggregate gradations, form geometry, and reinforcement configurations. Please consult your local Grace Construction Products representative for assistance with developing mix designs for Self-Consolidating Concrete.

Compatibility with Other Admixtures

ADVA Cast 555 is compatible in a concrete mix with all Grace admixtures, including all air entraining agents. Each admixture should be added separately into the mix.

Dispensing Equipment

A complete line of accurate, automatic dispensing equipment is available.

Packaging

ADVA Cast 555 is available in bulk, delivered by metered trucks, in 1041 L (275 gal) totes, and 210 L (55 gal) drums. ADVA Cast 555 will freeze at approximately 0°C (32°F) but will return to full functionality after thawing and thorough mechanical agitation.

Specifications

ADVA Cast 555 is supplied as a ready to use brown liquid, one liter weighs approximately 1.07 kg (one gallon weighs approximately 8.90 lbs). ADVA Cast 555 contains no intentionally added chlorides.

The superplasticizer shall be ADVA Cast 555 as manufactured by Grace Construction Products, Cambridge, MA.

North American Customer Service: 1-877-4AD-MIX1 (1-877-423-6491)

Visit our web site at: www.graceconstruction.com

W. R. Grace & Co.-Conn. 62 Whittemore Avenue Cambridge, MA 02140

PRODUCT INFORMATION

Daratard® 17

Initial Set Retarder ASTM C494, Type B and Type D

Description

Daratard® 17 admixture is a ready-to-use aqueous solution of hydroxylated organic compounds. Ingredients are factory premixed in exact proportions to minimize handling, eliminate mistakes and guesswork. Daratard 17 admixture weighs approximately 1.17 kg/L (10.2 lbs/gal).

Uses

Daratard 17 retards the initial and final set of concrete. At the usual addition rate of 195 mL/100 kg (3 fl oz/100 lbs) cement it will extend the initial setting time of portland cement concrete by 2 to 3 hours at 21°C (70°F). Daratard 17 is used wherever a delay in setting time will insure sufficient delivery, placement, vibration or compaction time, such as in:

- Hot Weather Concreting
- Transit Mix Concrete
- Prestressed Concrete

Daratard 17 is also used in special applications, as in bridge decks where it extends plastic characteristics of the concrete until progressive deflection resulting from increasing loads is completed.

Water-Reducing Properties

Along with set retardation, Daratard 17 provides water-reduction (typically 8 to 10%) in a concrete mix. This water-reducing action of Daratard 17 produces greater plasticity and workability in the fresh concrete and the strength and permeability of the hardened concrete are measurably improved. Daratard 17 is designed for use on jobs where high temperatures or extended setting times are the prime factors. It is recommended only when the primary purpose is to delay and control the setting time of concrete. When time and temperature are not major considerations, Grace Construction Product's water-reducing admixtures such as WRDA® with HYCOL® should be used.

Compatibility with Other Admixtures

Daratard 17 is compatible in concrete with all commercial air- entraining admixtures, such as Daravair®. Due to the slight air-entraining properties of Daratard 17, itself, the addition rate of Daravair may be reduced by about 25%. Each admixture should be added separately.

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Addition Rates

Addition rates for Daratard 17 will range from 130 to 520 mL/100 kg (2 to 8 fl oz/100 lbs) of cement. The amount to be used will depend upon the degree of retardation required under job conditions. Longer setting times or higher temperatures will require higher addition rates. Conversely, the addition rate will be lower for shorter extensions of time.

Dispensing Equipment

A complete line of accurate, automatic dispensing equipment is available. Daratard 17 may be introduced to the mix with the sand or with the water.

Packaging

Daratard 17 is available in bulk, delivered by metered tank trucks, and 210 L (55 gal) drums. Daratard 17 will freeze at about -2°C (28°F), but will return to full strength after thawing and thorough agitation.

Architects' Specification for Concrete Retarding Admixture

Concrete shall be designed in accordance with ACI Standard Recommended Practice for Selecting Proportions for Concrete (ACI 211.1).

The set-retarding/water-reducing admixture shall comply with ASTM Designation C494, Type D admixture, and shall be Daratard 17, as manufactured by Grace Construction Products, or equal. Certification of compliance shall be made available on request. It shall be used in strict accordance with the manufacturer's recommendations.

The addition rate shall be adjusted to produce the specified retardation of the concrete mix at all temperatures.

North American Customer Service: 877-4AD-MIX1 (877-423-6491)

Visit our web site at: www.graceconstruction.com

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