Final Report

Evaluation of Self-Consolidating Concrete (SCC) for Use in North Dakota Transportation Projects

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EXPERIMENTAL PROJECT REPORT

EXPERIMENTAL PROJECT	EXPERIMENTAL PROJECT NO. 1	STATE: UND	Y EAR: 2008	-	NUMBER: 02	SURF:	CONSTRUCTION PROJ NO 8 / LOCATION Grand Forks 28
	EVALUATION FUNDING 48	1 X HP&R	2 CONSTRUCTION	3 DEMONSTRATION	4 IMPLEMENTATION	NEEP NO. 49	PROPRIETARY FEATURE? Yes / 51 X No
SHORT TITLE	TITLE 52	Evaluation of Self-Consolidating Concrete (SCC) for Use in North Dakota Transportation Projects					
THIS FORM	DATE 140	MO. 12	--	YR. 2010	REPORTING 1 INITIAL	2 ANNUAL	3 X FINAL

KEY WORDS	KEY WORD 1 Concrete 145	KEY WORD 2 Structures 167
	KEY WORD 3 Self Consolidating 189	KEY WORD 4 211
	UNIQUE WORD 233 SCC	PROPRIETARY FEATURE NAME 255

	Date Work Plan Approved	Date Feature Constructed:	Evaluation Scheduled Until:	Evaluation Extended Until:	Date Evaluation Terminated:
CHRONOLOGY	11/2008				9/2010
	277	281	285	289	293

	QUANTITY OF UNITS (ROUNDED TO WHOLE NUMBERS)	UNITS	UNIT COST (*Dollars, Cents*)
QUANTITY AND COST	Lab work, Technology Transfer Events, & Final Report	1 LIN. FT 2 SY 3 SY-IN 4 CY 5 TON 6 LBS 7 EACH 8 X LUMP SUM	$47,450
	297	305	306

	CONSTRUCTION	PERFORMANCE	FINAL
AVAILABLE EVALUATION REPORTS	315		9/2010

	CONSTRUCTION PROBLEMS	PERFORMANCE
EVALUATION	318 1 NONE 2 SLIGHT 3 MODERATE 4 SIGNIFICANT 5 SEVERE	319 1 EXCELLENT 2 GOOD 3 SATISFACTORY 4 MARGINAL 5 UNSATISFACTORY

APPLICATION	320 1 ADOPTED AS PRIMARY STD. 2 PERMITTED ALTERNATIVE 3 ADOPTED CONDITIONALLY	4 X PENDING 5 REJECTED 6 NOT CONSTRUCTED	*(Explain in remarks if 3, 4, 5, or 6 is checked)*
REMARKS	321 SCC has not been added to NDDOT specifications. The use of SCC will be considered on a case-by-case basis 700		

Form FHWA 1461

DISCLAIMER

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EXECUTIVE SUMMARY

The purpose of this research project is to evaluate self-consolidating concrete (SCC) for use in North Dakota transportation projects. SCC is a concrete that can be placed and compacted under its self-weight with little or no vibratory effort, while remaining homogeneous and cohesive throughout the placing process without segregation or bleeding. To gain a better understanding of SCC properties, there is an immediate need for a comprehensive evaluation of the technology under North Dakota conditions and the development of construction specifications. Therefore, SCC will be evaluated and suggested acceptance criteria will be established. It is anticipated that the findings of the investigation will serve as a significant progress in the application of SCC in the North Dakota transportation projects.

This research project was conducted to evaluate the plastic and hardened properties of SCC as compared to conventional (normal) concrete (NC) mixes with the same mix proportions. A state department of transportation (DOT) survey was conducted on the present use of SCC in transportation structures. A total of six mixes were subjected to the testing program, including three NC and three SCC mixes. In particular, three pairs of mixes were compared on an individual basis and collectively as a group. For each pair of mixes the cementitious material, aggregate proportions, and water to cement ratio were held constant. Moreover, the water to cementitious ratio and the fine to total aggregate ratio were held constant for all mixes; the only parameters that could be varied were the admixture dosages.

Many strength parameters were tested but properties such as bond strength, tensile strength, permeability, and air void structure were of high interest due to the variability of performance of SCC in past research. ASTM criteria were used to qualify SCC mixtures in the plastic state; namely the slump flow test, slump flow with J-Ring, and column segregation test. The technical advisory committee that was comprised of a principal investigator (PI), personnel from the University of North Dakota (UND), the North Dakota Department of Transportation (NDDOT), Strata Corp., Midwest Testing Laboratories, and the North Dakota Ready-mix Association determined the final mix proportions. The technical advisory committee realized that the final mix proportions used in this research do represent the lower bound in terms of cementitious material used in practice today. It is expected that

the results of this research along with the state DOT survey responses will aid the NDDOT in writing their own specification for use of SCC in transportation infrastructures.

In this project river gravel was used for coarse aggregate and it is representative of the typical aggregate used on NDDOT projects. BASF Admixtures provided the chemical used in the project, which includes air-entrainment (AAE), viscosity modifying admixture (VMA), high range water reducing admixture (HRWRA), and water-reducer (WR). Type I/II cement and class C fly ash were used as cementitious material.

This research proved that SCC could be produced with adequate strength and stiffness in comparison to conventional concrete. SCC mixes had high amounts of HRWRA that dispersed cementitious material more uniformly and allowed for thorough hydration. In general SCC had as good or better strength (compressive, tensile, shear, bond) and stiffness (modulus of elasticity). SCC had a questionable air-void system due to a high spacing factor in two out of the three SCC specimens tested. The two specimens with a coarse air void system were slightly over the spacing limit of 0.008" (failing specimens each had a spacing factor of 0.01"). The upper limit used to be 0.01" until ACI 201 arbitrarily lowered the limit to 0.008". SCC also had slightly higher permeability but was still classified as "low" per ASTM C1202. Plastic state observations indicate that a slump flow of 22-26 incheswas adequate to obtain good consolidation and surface finish when pouring ASTM A944 pullout blocks.

Future research could investigate a way to improve the air-void structure, though past research by Khayat, et al. [14] suggested that increasing the cementitious content and/or decreasing the water to cement ratio would yield results that meet ACI 201 criteria. A more elaborate study on bond could be performed as well; the findings of this research indicate that the bond of SCC to rebar is adequate. Different embedment lengths at varying heights from the top of the form could be used to examine if the top bar effect is a concern.

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1.0 LITERATURE REVIEW

1.1 Background

The majority of concrete relies on compaction for casting; if not compacted properly, air voids develop and lead to concrete with inadequate strength and durability. Not only is it difficult to ensure concrete is fully compacted with the use of mechanical vibrators, sometimes this "full compaction" will not even occur. In search of other ways to obtain compaction, research in the mid-1980s throughout the UK focused on underwater concrete, in situ concrete piling, and filing of inaccessible locations [1]. The development of water-reducing superplasticizers allowed for achievement of workable, high-strength concrete. However, aggregate segregation, excessive bleeding, and inadequate slumps were observed, so use of these admixtures became limited. Failure of this underwater placement idea resulted in the development of self-consolidation concrete (SCC), or self-compacting concrete [1].

Arriving as a revolution in the field of concrete technology, this concept was proposed by Professor Hajime Okamura of Kochi University of Technology, Japan in 1986 as a solution to the growing concerns of concrete durability in Japan [2]. During his research, Okamura found that the main cause of poor durability of Japanese concrete structures was inadequate consolidation of concrete in casting operations. Adequate compaction by skilled workers is essential in the creation of durable concrete; due to a consistent reduction in the number of skilled workers in the construction industry in Japan, construction quality and concrete durability also consistently declined [2]. By developing concrete that self-consolidates, Okamura eliminated the need for numerous skilled workers and the main cause for poor durability performance of their concrete.

By 1988, prototypes of SCC were developed and ready for the first real-state tests [2]. Due to its satisfactory performance with regard to several properties, including drying and hardening shrinkage, it was deemed as "high performance concrete." This term has since been linked to high durability concrete with low water-cement ratios, and can also be named "self-compacting high performance concrete" [2]. The first paper on SCC was presented at the second East-Asia and Pacific Conference on Structural Engineering and Construction

(EASEC – 2) in 1989 [2]. Another presentation was given at an Energy Diversification Research Laboratories (CANMET) /American Concrete Institute (ACI) meeting in 1992, and in 1997, a RILEM (Réunion Internationale des Laboratoires et Experts des Matériaux) committee (TC 174) on SCC was founded [2]. Today, SCC is studied worldwide and further developments continue to be made; papers on this topic are presented at almost every concrete-related conference [2-10]. Not only is SCC commonly researched and studied, structures around the world are now incorporating SCC in areas where conventional concrete is not feasible.

1.2 Definition of SCC

According to ACI Committee 237, SCC is a highly flowable, non-segregating concrete that can spread in place, fill formwork, and encapsulate the reinforcement without any mechanical consolidation [11]. Its basic properties include filling ability, passing ability, and stability. In other words, SCC can flow freely through tight openings; it passes through and bonds to reinforcement material, such as steel reinforcing bars. In addition, SCC spreads into place and fills spaces within the formwork under its own weight with little or no mechanical vibration. Figure 1 depicts a concrete structure and shows how well SCC fills precast forms.

Figure 1: SCC easily fills precast forms

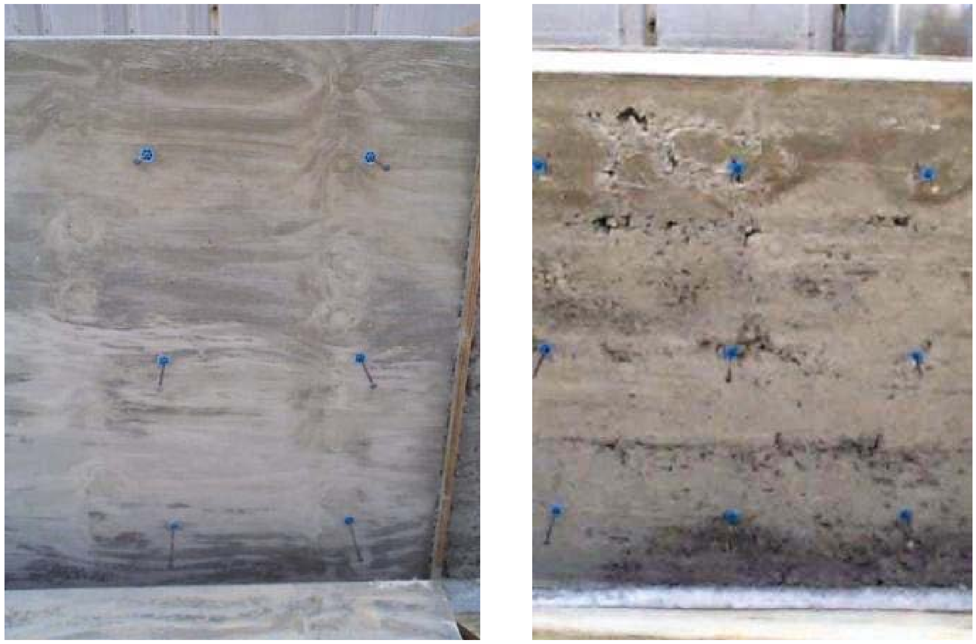
Furthermore, SCC remains cohesive throughout transport and placing without aggregate segregation or bleeding and is very workable because it remains stable during and after placement.

1.3 SCC Characteristcs

Stemming from its numerous favorable properties, use of SCC brings forth many benefits and advantages. SCC's high level of flowability creates defect free, uniform surfaces, without need for additional surface refinishing. In result, SCC is a viable option for aesthetic architectural design. Due to its ability to move freely into and easily fill constricted spaces, consolidation around reinforcement is improved, along with pumpability and uniformity. An example of pumpability is shown in Figure 2; due to lack of overhead clearance, SCC is pumped from the bottom into steel tubular columns.

Figure 2: SCC can be pumped into hollow steel tubular columns [12]

In addition, eliminating vibration cuts down on the labor needed and speeds up construction, resulting in faster placement rates, cost savings, and less traffic disruptions. Reduction of equipment usage lessens wear and tear, reduces noise level in concrete plants and at construction sites, and improves jobsite safety. Lack of vibration, furthermore, reduces aggregate segregation, honeycombing, and voids in the concrete. Figure 3 displays two pictures of placed concrete; Figure 3a shows concrete placed without vibration, while Figure 3b shows concrete placed with vibration. The mechanical vibration segregates the aggregate in the concrete and disrupts the smooth surface. SCC, on the other hand, experiences no vibration and has a smooth finish.



(a) (b)

Figure 3(a): Concrete placed without mechanical vibration

Figure 3(b): Concrete placed with mechanical vibration [12]

The overall concrete quality is improved as problems associated with vibration, such as under vibration, over vibration, or damage to the air void structure, are eliminated. The concrete's resistance to chloride intrusion and ability to withstand freeze-thaw damages are also improved with the use of SCC. Another advantage of SCC stems from advances in high range water reducing admixtures (HRWRA) and viscosity modifying admixtures (VMA). Instead of the previous susceptibility to shrinkage and reduced shear capacity, SCC, with the addition of HRWRA and/or VMA, can now evolve into a mix with desired fresh properties and adequate mechanical properties as compared to NC mixes with similar aggregate and water content. As noted, SCC has many favorable characteristics that make it a viable construction material.

1.4 Application of SCC

SCC is commonly used in place of conventional concrete for better, faster, and cheaper construction. According to Okamura, “Whatever conventional concrete can do, SCC can do better, faster, and cheaper, especially for concrete elements with special textures, complex shapes, and congested reinforcements” [2]. More examples of worldwide SCC use are found within precast and cast-in-place construction and throughout structural and architectural concrete elements where reinforcing steel is tight and/or surface smoothness is important. Other implentations of SCC include drilled piers, caissons, bridge abutments and walls.

While European countries are rapidly adopting the technology for the construction of bridges and structures, concrete admixture manufacturers were the first to introduce SCC in the United States for precast and cast-in-place applications. Now, applications of SCC by transportation agencies have included bridges built in New York, Virginia, Nebraska, and other states. A National Cooperative Highway Research Program (NCHRP) project (No. 18-12) is also underway to develop SCC mixes, structural design parameters, and construction specifications for precast, prestressed concrete elements.

1.5 Case Studies

In order to gain a better understanding of SCC uses throughout the nation, a more thorough investigation of several case studies will be presented.

Recently, the New York State Department of Transportation (NYSDOT) has used substantial amounts of SCC. Current projects include the use of SCC for prestressed, high-performance concrete bridge beams on the Brooklyn-Queens Expressway from 61st Street to Broadway in New York City [4] and in the reconstruction of the East Tremont Avenue Bridge over the Cross Bronx Expressway. NYSDOT plans to use SCC for a majority of the precast substructure components for the replacement of the Roslyn Viaduct Bridge, just outside of New York City. According to a NYSDOT official, "The performance of SCC has been excellent. NYSDOT is achieving very good quality with a minimum of defects. There has been a slightly higher cost for admixtures, but “NYSDOT saves on labor” [4]. Clearly, SCC has become a highly endorsed version of concrete in New York because it reduces costs while still meeting necessary construction requirements.

In addition to NYSDOT, the Virginia Department of Transportation (VDOT), a leader in developing SCC technology in North America, is using SCC for precast, prestressed, and cast-in-place applications. One of their first projects involved the use of SCC in the Pamunkey River Bridge (PRB) Project with Celik Ozyildirim as the principal investigator. The purpose of this study was to construct and evaluate the overall performance of SCC in bulb-T beams in Route 33 over the Pamunkey River in Virginia. Figure 4 displays an image of several of the eight prestressed SCC beams that were used in one span of the new Route 33 Bridge.

Figure 4: SCC girders support the PRB [13]

Before the construction of the bridge beams, two full-scale test beams, 22.5-m (74-ft) long, were prepared and tested. The mix design used for these beams is outlined in Table 1.

Table 1: Mix design for PRB beams

Material	SCC	Control
PC	480	510
Slag	320	340
CA size	#78	#68
CA	1451	1731
FA	1411	1029
Water	272	336
w/cm	0.34	0.40
VMA (fl oz/yd^3)	16	----
Retarding (fl oz/yd^3)	24	27
HRWRA (fl oz/yd^3)	96	66
Calcium Nitrite (gal)	2	2

During production, Ozyildirim noted that free moisture was not monitored closely in aggregates, resulting in the rejection of several truck loads of SCC. Air voids were found in both the control and SCC beams when the formwork was stripped off, but were less prevalent in the SCC beams. He offered five ways to improve the SCC mix, including the use of well-graded combined aggregates, fine aggregate with a lower void content, and VMA with the appropriate dosage. In addition, he recommended using more fine material and minimizing the specific gravity difference between the coarse and fine aggregate.

Plastic state tests performed include slump flow, T_{20}, air content, and U-box flow, and the results obtained from these tests are shown in Table 2.

Table 2: Plastic state test results for PRB beams

Batch	Date	Concrete	Slump Flow (in)	T20 (sec)	Slump (in)	Air (%)	U-Box Flow (in)	Concrete Temp (F)
B1	08/15/2005	SCC	22	2.8		5.3	12	88
B2	08/15/2005	SCC	23.7	3.2		5.6	9.8	86
B3	08/15/2005	Regular			8.0	4.2		86
B4	08/15/2005	Regular			6.3	4.5		87
B5	08/17/2005	SCC	27			4.5	13.3	82
B6	08/17/2005	SCC	21			5.0	13.3	84
B7	08/17/2005	SCC	23			5.2	12.8	84
B8	08/19/2005	SCC	19.5			4.5	10.8	
B9	08/19/2005	SCC	27			4.5	13.3	

Neither the SCC beams nor control beams provided proper resistance to freezing and thawing because both contained a poor air void structure, attributable to polycarboxylate HRWRA. This problem can be fixed, according to Khayat [14], Persson [15], and Beaupre et al. [16], with the use of VMA; it increases mix stability and does not allow air entrainment to escape as the mix sets.

The test beams were tested for transfer and development length, as well as shear and flexural strength. The field evaluations included the fabrication and placement of SCC and conventional non-SCC concrete, instrumentation of bridge beams with strain gages and thermocouples (in order to compare their performance with that of regular concrete beams), testing of specimens cast during placement, and the measurement of strain and camber over time [13]. The hardened properties are listed in Table 3.

Table 3: Hardened state test results for PRB beams

Property	Age (d)	B1 (SCC)	B2 (SCC)	B3 (Control)	B4 (Control)
Compressive Strength (psi)	2	7,470	6,650	6,270	5,790
	7	9,170	8,860	7,760	6,960
	28	10,110	10,700	7,960	7,610
Elastic Modulus (10^6 psi)	2	5.07	4.54	4.99	4.52
	7	5.10	5.06	5.45	5.15
	14	5.00	5.19	5.69	5.16
	28	4.86	5.35	5.26	4.98
Splitting Tensile Strength (psi)	7	760	695	715	650
	28	820	755	675	565
Permeability (coulombs)	28	869	996	1,011	985

Overall, VDOT feels “the eight beams have very good strength, low permeability, and are performing well” [5].

In Nebraska, the Department of Roads is using SCC for applications such as long-span and short-span bridge girders, pilings, and temporary Jersey barriers. These projects using SCC have included the new Skyline Bridge in Omaha, Nebraska. Completed in 2004, this project features a full-width bridge deck made of SCC. SCC exhibits very good performance, with shorter construction periods. The time it takes to fill forms, for example, has been reduced about twenty-five percent [6].

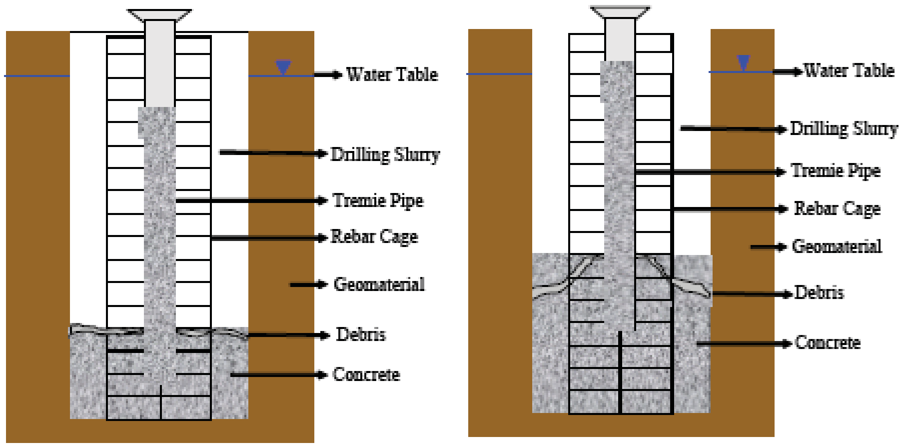
Looking further into SCC usage, drilled shafts also commonly use SCC. Schindler et al. [17] discuss several problems with the use of conventional concrete in drilled shafts. It is reported that experienced workers often describe the quality of drilled shaft concrete, usually conventional high slump concrete, as a creamy paste rather than a boney texture. This paste consistency makes the drilled shaft concrete susceptible to aggregate blocking around the rebar cage, displayed in Figure 5.

Figure 5: Drilled shaft not encapsulated by concrete [19]

Another problem with conventional concrete stems from the interruptions in concrete supply during placing. These interruptions decrease workability of the concrete within the shaft. Figure 6 displays a drilled shaft with defects due to loss of workability.

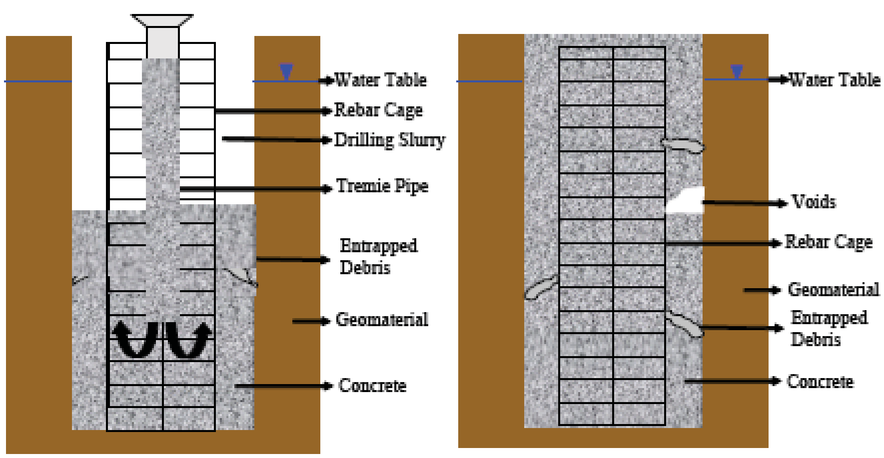
Figure 6: Drilled shaft with defects due to loss of workability

In addition to causing defects to the drilled shaft, placement interruptions can result in entrapped debris on the outside of the rebar cage. As the reinforcement ratio in a drilled shaft increases, a higher probability for entrapped debris outside the rebar cage exists. This occurs when the lateral flow of the concrete is impeded, described as screening of concrete, and results in an elevation difference between the inside and outside of the rebar cage. An example is outlined in Figure 7.



A) Fresh concrete with sufficient workability being placed within the shaft.

B) Interruption in concrete supply allows concrete to lose its workability in the shaft.



C) After concrete placement resumes, the fresh concrete that is introduced erupts through the stiff concrete and entraps debris on the outside of the rebar cage.

D) Completed shaft may contain large pockets of entrapped debris and voids.

Figure 7: Interruptions in concrete placement causing debris entrapment

Schlinder [17] aimed to develop and test a SCC mix to use in drilled shaft construction to eliminate the problems associated with normal concrete mixes. Past research by PCI helped determine initial performance requirements, and S&ME, Inc. of Mt. Pleasant, South Carolina performed full scale testing for Auburn University and the SDDOT [18]. Four, six-foot diameter drilled shafts were constructed with both SCC and conventional concrete. Two of the shafts, one of SCC and one of conventional concrete, were exhumed, sawed, and cored, and non-destructive testing was performed. Observations included proper aggregate distribution of the concrete in the sawed sections and no major air voids. In addition, it was determined that permanent casing should not be used because it does not allow bleed water to flow out laterally; the bleed water only flowed upward, resulting in greater shaft damage. The SCC and conventional mix shafts were loaded to the same amount and showed very similar displacements, resulting in the conclusion that SCC can be used in place of conventional concrete. Also, since workability must be maintained during the pour of drilled shaft concrete SCC is a natural fit; SCC is highly flowable and maintains workability throughout placing. William M. Campbell, III, a registered PE in South Carolina and the Technical Principal of S&ME, concluded the investigation by saying,

> "Based on the performance of SCC used in this project, we believe it is a good choice for use in drilled shaft construction in South Carolina. The higher slump flow and subsequent easier workability could prove useful where seismic demands result in closely spaced horizontal reinforcement" [19].

Similarly, it has been noted that bridge deep foundations in Ohio and other eastern states are almost always constructed of drilled caissons rather than steel H piling as used in North Dakota. It was mentioned at the SCC Workshop in Fargo in April of 2007 that highly fluid concrete mixes (like SCC) are very important in the successful construction of drilled cassion installations.

Not only has SCC developed a strong presence in the United States, several European countries formed a consortium in 1996 to develop SCC for practical applications in Europe. Over the past five years, SCC bridges and structures have been constructed in several countries including the Netherlands, Sweden, and United Kingdom. In particular, SCC has been used in the Sodra Lanken project in Stockholm, which is the largest ongoing infrastructure project in Sweden. The project will provide a 6-km (3.7-mi) four-lane link from West to East in the southern part of the city. It includes seven major junctions, with bridges, earth retention walls, tunnel entrances, and concrete box tunnels.

1.6 Research on SCC

While SCC usage continues to expand its awareness and usage worldwide, research on the subject is ongoing. For example, many research projects have been developed to test SCC mixes comprised of fifty percent sand [11, 20]. Results show that this SCC exhibits more than adequate compressive strength, though also displays increased shrinkage, reduced modulus of elasticity, and reduced shear strength. Despite the reduction of modulus of elasticity and shear strength, SCC mixes with fifty percent sand may still be acceptable for use. However, in order to use these SCC mixes, they must be produced with adequate bond strength, compressive/tensile strength, durability, and shrinkage resistance in flexural and/or combined flexural-axial loading situations [11, 20].

A closer look of SCC mix types and variations of these mixes has also been a common research topic. The three types of SCC mixes include Powder type, VMA type, and Combination type [11]. Powder type SCC mixes incorporate large amounts of cementitious material along with HRWRA. VMA types, on the other hand, tend to use moderate amounts of cementitious material, fair amounts of rock, and both HRWRA and VMA. VMA is required to hold the mix together, while HRWRA is often incorporated to extend the spread to a range of twenty-four inches to twenty-eight inches. In theory, a VMA type mix should mechanically perform better than a powder type mix because of its lower water-cement ratio and larger coarse aggregate content; these characteristics restrain shrinkage and improve shear capacity. Combination type mixes use a combination of characteristics from powder and VMA type mixes. Regardless of the mix type, it is important to note that the mix itself must always be designed for a specific application [11].

Research has also been done on the use of SCC in prestressed/precast beams. Most notably, full-scale testing has been performed at the University of Minnesota, Lehigh University in Pennsylvania, and Kansas State University [21, 22, 23, 24]. Lehigh University also performed comprehensive mechanical testing before choosing final mix proportions on the prestressed beams. The results show that precast plants should produce SCC water-cement ratios of 0.32-0.40 [11]. Increasing the water content any more causes stability problems. However, the research also proves that these problems can be controlled with VMA, or by increasing fine aggregate content.

In addition to SCC mix types and prestressed precast beams, vast amounts of research on SCC characteristics and factors affecting its performance are an important research topic. When compared to conventional mixes with identical aggregate sources, gradations, water-cement ratios, and identical curing conditions, a SCC mix will always have superior compressive strength due to the admixture alone [11]. These admixtures, including WR and HRWRA, disperse the cement particles more uniformly in the mix, resulting in more thorough hydration and denser microstructure. In addition, provided that the fine to total aggregate ratios are kept consistent with historically used values, the tensile and shear strengths of SCC surpass those of conventional concrete [11]. Flexural strength can conservatively be predicted using ACI 318-08 equation 9-10 ($7.5\sqrt{f_c^{'}}$), and research by Naito et al. at Lehigh University [22] convincingly proves that SCC mixes during full scale testing have a modulus of rupture greater than $7.5\sqrt{f_c^{'}}$.

SCC proves to possess adequate stiffness in well-proportioned mixes [25]. When deflection is a serious design concern, a conventional mix should be converted to a SCC mix with adequate coarse aggregate content. If there is a deficiency in coarse aggregate content, modulus of elasticity (MOE) prediction models (based on the square root of compressive strength) will be under-conservative. This is due to SCC's ability to produce high compressive strength, which directly affects modulus of elasticity. In result, structural engineers must be careful when using MOE prediction models for preliminary design. To avoid these problems, establish MOE in the trial batch phase, and relay the information to structural designers prior to use of SCC, especially in precast plants [25].

Since concrete has the highest workability immediately after mixing, workability retention is another issue with SCC. Different HRWRA have different effects on workability retention; set-retarders have been used to maintain slump flow but have some impact on bond strength [8]. ACI Section 5.10.4 allows a concrete mix to be re-tempered once with HRWRA at the jobsite; therefore when jobsites are located thirty to forty-five minutes from a batch plant, the mix will likely require the use of re-tempered concrete. One option suggested and tested by NDOR includes mixing SCC with only two-thirds the required HRWRA at the plant and mixing the remainder of the admixture once the concrete mix has been transported to the jobsite [20]. NDOR discovered through sample coring and testing that after jobsite re-tempering, sufficient flow was maintained and adequate air-void structure was in place.

Another issue arises with the use of HRWRA because high amounts of this admixture create coarse air-bubbles within the hardened mix [11] that push the spacing factor above the limit of 0.008 inches set by ACI 201.2. Past studies on the interaction of HRWRA and AEA have shown that such air-void systems tend to be less stable and usually have larger spacing factors [26, 27]. Yet, research by Litvan et al. [27] proved specimens with a spacing factor greater than 0.008 inches can still maintain adequate durability. In effort to discover new ways to stabilize the air void system, Khayat et al. [28] produced SCC mixes with spacing factors of 0.008 inches or less. He found that increasing the total cementitious content and/or decreasing water-cement ratios can indeed provide stabilization. Khayat also found that for mixtures with a relatively low content of cementitious materials and a high water-cement, the air-void stability increases when a VMA is incorporated.

Furthermore, the permeability and diffusivity of SCC depends on the mixture proportions. Low water-cement ratios and frequent use of supplementary cementitious materials (SCM) are favorable for improving permeability and diffusivity. However, not all SCMs have the same effect [11], and one disadvantage of SCM use is delayed strength gain, which is not desired for obtaining an early high strength.

ACI 237 states, "the bond of SCC is equal to or greater than conventional concrete," but is only relevant if SCC is produced with little or no bleeding. Research performed by Peterman et al. [23, 24] proves that SCC members have been produced with greater nominal moment capacities than design calculations provided by PCI design procedures and classic strain compatibility relations.

Also, research shows that SCC has improved transfer lengths [22]. More specifically, Staton et al. [29] found measured transfer lengths to be about sixty percent of those predicted by ACI 318-05 and AASHTO LRFD Bridge Design Specifications equations. These increased lengths can occur if SCC mixes are made with inadequate amount of rock or if set-retarders are introduced into the mix. Transfer length represents the distance needed along a member to transfer the prestressing force. It can be calculated by:

$$\frac{f_{se}}{3000} d_b \quad (\text{ACI } 318-08 \text{ Figure } R12.9) \tag{1}$$

where:

f_{se} =effective prestress in prestressing steel, MPa, and

d_b = thickness, in.

In summary, even though SCC has become a well-known replacement for conventional concrete, ongoing research about the subject will still take place. Past research has proved useful in the development of SCC mixes and a continuous search for new information will only help to improve the mix design.

2.0 DOT SURVEY RESULTS

A fifty state survey, consisting of six questions, was sent out to all state departments of transportation (DOT). The purpose of the survey was to gage the use of SCC in transportation structures around the United States. The survey read as follows:

1.) Does your state use SCC?
2.) If yes, in what applications are you currently using SCC?
3.) Does your state have a specification for SCC?
4.) If yes, how can we obtain a copy of your specification? If online, what is the address?
5.) Please provide contact information for additional technical information on your state practices?
6.) Has your state previously conducted research on application of SCC?

If yes, please provide:
Report No. ___________________________
Title: _______________________________
Location Online: ____________________

Based on the survey results, twenty-one state DOTs use self-consolidating concrete. Fourteen state DOTs use SCC in pre-stressed applications, and nine state DOTs use SCC in cast-in-place operations. There are eleven state DOTs with ongoing research; Nebraska and Virginia lead the way in research and plan to conduct more well into the next decade.

Several interesting responses were received from the DOTs. For example, California (CALTRANS) is using SCC on the San Francisco/Oakland Bay Bridge. They did not mention how or where they used SCC, but noted it was used where conventional concrete was not appropriate.

Colorado has no written specification, but is using SCC in a bridge repair job along I-25. With heavy traffic on the bridge, the concern was that the concrete would not be able to bond to the beams and existing concrete abutments. As a result, the existing steel plate girders were bonded to the abutments. Traffic was shut down to one lane at a time and work was performed in the early morning hours to minimize vibration. Conclusions from the report stated that SCC bonded very well to the steel plate girders and existing concrete, therefore deeming SCC as a viable option on bridge repair.

State DOT officials from Kentucky have developed a precast plant qualification process, serving as a model for other states. According to the specification, a precast plant must file a request that contains a minimum cementitious amount of 564 pounds per cubic yard and a maximum water-cement ratio of 0.46. In addition, a demonstration for the admixture and cement suppliers must occur in order to obtain a ninety day "learner's permit" that allows long term tests to take place and be monitored. It also requires the development of strength test history and makes sure stable mixes are produced consistently. The full specification is listed in the Appendix II.4.

In addition to California and Kentucky, Minnesota has used SCC in drilled shafts on I-35W, and the University of Minnesota is finishing its final SCC report. Also, Nebraska has developed a very general guide to cast-in place operations that recommends the use of ASTM C457 Linear Traverse testing method and a minimum of 588 pounds per cubic yard of Portland cement in a single batch.

Furthermore, New Jersey mainly uses SCC in drilled shaft construction. NJDOT created a detailed specification for drilled shaft construction that requires the contractor to verify certain characteristics of SCC. More specifically, the contractor must check for sufficient pumpability, a spread of twenty-one to twenty-four inches, and a fine aggregate content of less than fifty percent by weight of the total aggregate content. NJDOT has a separate specification for precast concrete, similar to its drilled shaft specification that allows for greater spread limits of twenty-four to twenty-eight inches.

South Dakota uses SCC in box culverts, while research is underway for use in prestressed bridge beams. South Dakota also imposes the following requirements on application of SCC: a maximum drop height of five feet and a ninety minute time limit after initial mixing for discharge of SCC.

Texas relies on PCI TR-6-03 as their complete specification, while, on the other hand, Virginia has a wealth of information on SCC and a very good specification that can be adopted. This specification states that a contractor must employ a SCC technologist with experience in proportioning, batching, testing, and placing SCC whenever pouring SCC. The engineer must also approve the SCC technologist prior to employment. The specification is intended for structural members and allows for a maximum permeability of 1500 Coulombs measured by ASTM C1202 at twenty-eight days. It also states the maximum shrinkage at twenty-eight days must be four percent and slump should settle between twenty-two and twenty-eight inches.

Washington has incorporated SCC into standard specifications for use in precast concrete barriers. A report on full scale testing of two, six feet diameter, fifty feet deep drilled shafts will be released in 2010, paving the way for their incorporation of SCC in drilled shaft construction.

After reviewing the state agency survey results and analyzing each state's responses, several conclusions can be made. SCC is most commonly used in mass structural applications, like drilled shafts, where compression loads are large. In addition, SCC may be used in precast members and prestressed beams, as early research has encouraged, but more full scale testing should be performed prior to use. Mixes should be prequalified by performing small scale mechanical testing, and bond strength should be the main component tested.

Hiring a SCC technologist who has met criteria developed by the DOT is important and a necessity whenever SCC is being produced or placed. Training programs should be introduced by PCI certified plants or ready-mix producers for production and construction crews in order to develop more SCC technologists; presently, there are too few trained individuals who have experience with flowable mixes. Most SCC technologists today are employed by admixture suppliers and can provide guidance for precast plants interested in using SCC.

Furthermore, survey results suggest that slump flows of twenty-one to twenty-four inches are adequate for drilled shaft construction, where as stressed precast or cast-in-place operations require larger spreads of twenty-four to twenty-eight inches. Air void stability also needs to be taken into consideration. To ensure proper stability, SCC should be designed with a minimum amount of VMA; a large amount will siphon the air entrainment. A minimum amount of HRWRA can be used in place of VMA, but both should come from the same admixture supplier. Not only should DOTs focus on slump and air void stability, but other performance based requirements should be a top priority. Some of these include compressive strength, modulus of rupture, drying shrinkage at twenty-eight days, rapid chloride ion permeability, maximum water-cement ratio, and column segregation during the trial batching phase.

These results, as you can see, have presented very useful information about SCC. Yet many uncertainties in this field will continually provoke more research. One topic that requires more investigating is the long-term performance of SCC mixes; more information will aid in estimation of deflection due to sustained loads (creep), prestress losses, and transfer length. Also, bond strength studies have experienced difficulties with transfer lengths [19], so further research will help improve results and explain factors affecting bond strength. Finally, a more extensive exploration of SCC can lead to the creation of proportioning guidelines in order to obtain adequate durability and air-void structure.

3.0 RESEARCH PROGRAM AND MIX DESIGN

A technical advisory committee consisting of the PI and personnel from UND, ready-mix producers, testing agencies, and NDDOT representatives coordinated and organized this research program. The scope of this research project is limited to the use of materials currently used by North Dakota concrete manufacturers for ready mix concrete in addition to SCC specific admixtures. The goal of this project is to evaluate the engineering properties of SCC as compared to conventional concrete, and to determine if SCC is acceptable for use. This project also aims to promote the development of acceptance criteria while educating specifiers and contractors about appropriate requirements for plastic and hardened properties and performance of SCC.

In order to obtain reliable results on SCC performance, a number of variables were held constant. More specifically, the water-cement ratio was held at 0.41 and the fine aggregate to total aggregate ratio remained at 0.43.

Strata Corporation provided the aggregate and admixture for this project, and The Lafarge North America provided the cementitious material. The material sources are listed in Table 4.

Table 4: Material sources

Materials	Source
Cement	Lafarge, Sugar Creek Type I/II - conforming to ASTM C150
Fly Ash	Headwaters, Coal Creek Station Class C - conforming to ASTM C618
Fine Aggregate	Strata Coporation, Pit #218 Marcoux, MN -conforming to ASTM C33
Coarse Aggregate	Strata Coporation, Pit #225 Trial, MN -conforming to ASTM C33
Intermediate Aggregate	Strata Coporation, Pit #218 Marcoux, MN -conforming to ASTM C33
High Range Water Reducer	BASF Admixtures, Master Builders, Glenium PS1466
Water Reducer	BASF Admixtures, Master Builders, Polyheed 1020
Viscosity Modifier	BASF Admixtures, Master Builders, Rheomac VMA UW 450
Air Entrainment	BASF Admixtures, Master Builders, MB AE 90

The NDDOT utilizes 6 and 6.5 bag mixes for cement, which are 564 lb/yd^3 and 611 lb/yd^3, respectively. In order to provide relevance to the NDDOT needs, the University of North Dakota took the Air Entrainment (AE) (6.0 bag) and Air Entrainment Admixture (AAE) (6.5 bag) mixes listed in the NDDOT Standard Specifications under Section 802 and converted them to SCC by using admixture and a well graded aggregate distribution. This project employs the mix designs listed in Table 5 after receiving input from the NDDOT and performing trial batching. A total of six mix designs were created and grouped in pairs; for each variation of cementitious bags and fly ash percentage, a normal concrete (NC) mix and a SCC mix was created. It was intended that any differences in the performance of SCC and its NC counterpart could be directly attributable to admixture usage and lack of mechanical consolidation.

The mix identification nomenclature is represented as, for example, NC:6.5:30FA, where NC stands for normal concrete, 6.5 represents the number of bags of cementitious material, and 30FA is the percentage of fly ash replacement by weight in cementitious material. SCC:6.0:30FA, on the other hand, reads self-consolidating concrete with 6.0 bags of cementitious material and thirty percent fly ash.

Table 5: Mix designs used in this project with target plastic properties

Material (lb/cyd)	NC:6.5:0.0FA	SCC:6.5:0.0FA	NC:6.5:30FA	SCC:6.5:30FA	NC:6.0:30FA	SCC:6.0:30FA
Cement (Lafarge, Sugar Creek, Type I/II)	611	611	428	428	395	395
Fly Ash, Lafarge Coal Creek	-	-	183	183	169	169
3/4" Rock	1370	1370	1370	1370	1415	1415
Pea Rock, 3/8"	355	355	355	355	340	340
Fine Agg.	1320	1320	1320	1320	1350	1350
Target Slump	3"	-	3"	-	3"	-
Target Spread		22-26"		22-26"		22-26"
Target Air	5-8%	5-8%	5-8%	5-8%	5-8%	5-8%
Target J-Ring	Within 2" of the spread w/o J-Ring					

Once the mix matrix was established, as listed in Table 5, a well-blended gradation was developed. The NDDOT has a special provision for well-graded aggregates; any blended gradation must meet the gradation limits listed in Table 6.

Table 6: NDDOT blended gradation limits

Composite Gradation Limits	
Sieve Size	Percent Passing
1"	100
3/4"	90 - 100
3/8"	55 - 70
# 8	31 - 42
# 16	18 - 35
# 50	0 - 10
# 200	0 - 3

The technical advisory committee suggested that the material retained on each sieve be between eight and twenty percent of the total material and that the percent retained gradation plot should resemble a bell curve. Three aggreagates, ¾" rock, ⅜" pea rock, and sand, were blended and their gradation was input into a spreasheet. The percentages of each aggregate type were adjusted to get the smoothest curve possible, resulting in Figure 8. This figure shows three different blends, but the two extra blend curves were used only for comparision. Blend 1 was used in the mix design and the exact blend used in this research project is listed in Table 7.

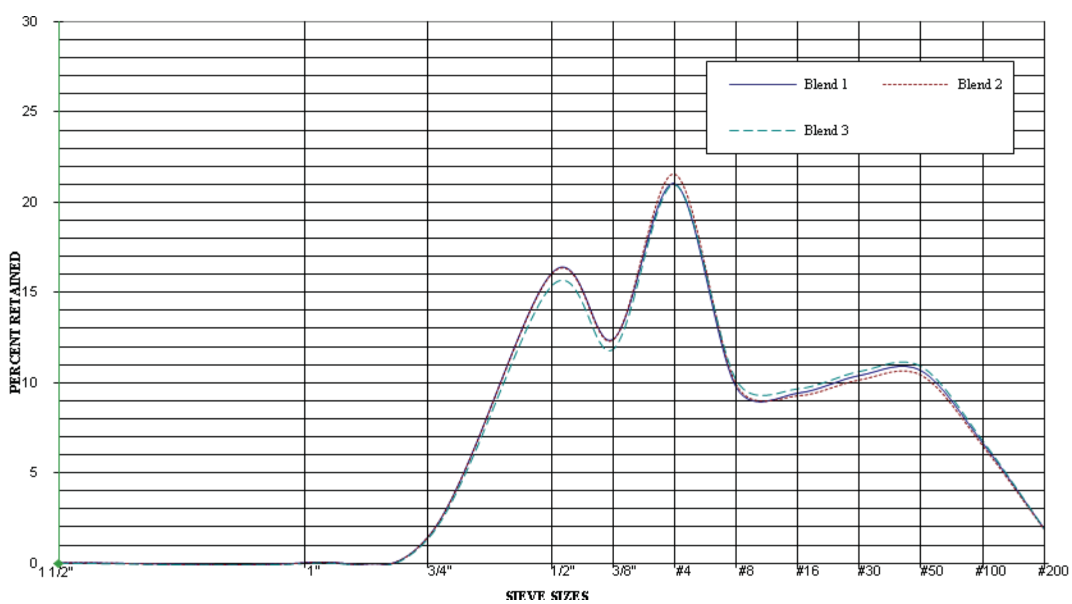


Figure 8: Gradation used for all mix design

Table 7: Gradation used for all mix designs

Sieve Size	% Passing
1 1/2 "	100
1"	100
3/4"	99
1/2"	83
3/8"	67
#4	49
#8	40
#16	33
#30	23
#50	10
#100	4
#200	1

The use of supplementary cementitious materials (SCMs) and a well graded aggregate distribution allowed the use of minimal admixture dosage to obtain desired flow for SCC mixes. During trial batches, it was observed that the viscosity modifying admixture (VMA) caused an increase in the amount of AEA demand. In most cases, only the High Range Water Reducer Admixture (HRWRA) was needed to produce a stable SCC mix regardless of total cementitious content. VMA was only used to provide extra stability or to increase the unit weight of the mix.

The exact mix proportions and admixtures used in this project are listed in Table 8. A total of twenty-five batches were used in casting hardened concrete test specimens, see Table 8.

Table 8: Mix proportions and admixtures

Trial	Mix ID	MB AE (oz. cwt)	Polyheed 1020 (WR) oz.cwt	Glenium PS 1466 (HRWRA) or Superplastizer	Rheomac 358 (VMA)	Batch Size	Notes
1	NC:6.5:0.0FA	0.34	4.20	-	-	1.50	1st Mix to hit
2	NC:6.5:0.0FA	0.36	4.20	-	-	3.50	Went in Blk 1
3	NC:6.5:0.0FA	0.30	4.20	-	-	3.50	Went in Blk 2
4	NC:6.5:0.0FA	0.25	4.20	-	-	3.50	Went in Blk 3
5	SCC:6.5:0.0FA	0.60	4.00	9.00	-	1.50	Cylinders
6	SCC:6.5:0.0FA	0.31	4.00	4.10		3.50	Blk 1
7	SCC:6.5:0.0FA	0.25	4.00	4.10	-	3.50	Blk 2
8	SCC:6.5:0.0FA	0.25	4.00	4.10	-	3.50	Blk 3
9	NC:6.5:30FA	0.32	0.20	-	-	1.50	Cylinders
10	NC:6.5:30FA	0.46	0.20	-	-	3.50	Blk 1
11	NC:6.5:30FA	0.55	0.20	-	-	3.50	Blk 2
12	NC:6.5:30FA	0.55	0.20	-	-	3.50	Blk 3
13	SCC:6.5:30FA	0.18	2.00	3.30	0.30	1.50	Cylinders
14	SCC:6.5:30FA	0.13	2.00	3.40	-	3.50	Blk 1
15	SCC:6.5:30FA	0.15	2.00	2.80	-	3.50	Blk 2
16	SCC:6.5:30FA	0.15	2.00	2.80	-	3.50	Blk 3
17	SCC:6.5:30FA	0.15	2.00	3.35	-	2.00	Extra Cylinders, mortar bars
18	SCC:6.0:30FA	0.15	2.00	4.50	-	2.00	Cylinders
19	SCC:6.0:30FA	0.15	2.00	5.20	-	3.50	Blk 1
20	SCC:6.0:30FA	0.17	2.00	5.20	0.10	3.50	Blk 2
21	SCC:6.0:30FA	0.15	2.00	2.80	0.10	3.50	Blk 3
22	NC:6.0:30FA	0.40	1.00	-	-	2.00	Cylinders
23	NC:6.0:30FA	0.24	0.55	-	-	3.50	Blk 1
24	NC:6.0:30FA	0.24	0.40	-	-	3.50	Blk 2
25	NC:6.0:30FA	0.26	0.30	-	-	3.50	Blk 3

For all 6.5 bag mixes (611 lbs cementitious)		Cement (Lafarge, Sugar Creek, Type I/II)	Fly Ash (Lafarge Coal Creek)	3/4" Rk	Pea Rk, 3/8"	Fine Agg.
	Weight (lbs/yd^3)	428.00	183.00	1370.00	355.00	1320.00

For all 6 bag mixes (564 lbs cementitious)		Cement (Lafarge, Sugar Creek, Type I/II)	Fly Ash (Lafarge Coal Creek)	3/4" Rk	Pea Rk, 3/8"	Fine Agg.
	Weight (lbs/yd^3)	395.00	169.00	1415.00	340.00	1350.00

The measured plastic properties of SCC including slump, spread, air content, unit weight, J-ring, VSI, and VBI, are listed in Table 9.

Table 9: Measured plastic properties of SCC

Trial	Mix ID	Slump (in)	Spread (in)	J-Ring (in)	Tare wt of Air bucket (lbs)	Volume of Air bucket (cf)	Wt of bucket and concrete (lbs)	Unit Wt (pcf)	Air Content %
1	NC:6.5:0.0FA	3.50	-	-	7.585	0.2501	43.95	145.40	5.50
2	NC:6.5:0.0FA	3.50	-	-	7.585	0.2501	43.20	142.40	7.80
3	NC:6.5:0.0FA	4.00	-	-	7.585	0.2501	43.05	141.80	8.00
4	NC:6.5:0.0FA	3.75	-	-	7.585	0.2501	43.80	144.80	6.00
5	SCC:6.5:0.0FA	-	22.00	20.75	7.58	0.2501	42.90	141.22	7.80
6	SCC:6.5:0.0FA	-	23.00	23.00	7.58	0.2501	42.85	141.02	7.40
7	SCC:6.5:0.0FA	-	23.75	23.25	7.58	0.2501	42.95	141.42	7.00
8	SCC:6.5:0.0FA	-	22.00	22.00	7.58	0.2501	43.35	143.02	6.60
9	NC:6.5:30FA	3.25	-	-	8.31	0.2485	44.05	143.82	6.80
10	NC:6.5:30FA	3.00	-	-	8.31	0.2485	44.80	146.84	5.20
11	NC:6.5:30FA	3.50	-	-	8.31	0.2485	44.55	145.84	6.00
12	NC:6.5:30FA	3.50	-	-	8.31	0.2485	44.25	144.63	6.20
13	SCC:6.5:30FA	-	22.50	22.00	8.31	0.2485	44.70	146.44	5.00
14	SCC:6.5:30FA	-	22.00	22.00	8.31	0.2485	44.50	145.63	5.50
15	SCC:6.5:30FA	-	21.50	21.50	8.31	0.2485	44.05	143.82	6.00
16	SCC:6.5:30FA	-	23.50	23.25	8.31	0.2485	44.30	144.83	5.50
17	SCC:6.5:30FA	-	23.00	22.50	8.31	0.2485	43.40	141.21	6.20
18	SCC:6.0:30FA	-	23.00	22.75	8.31	0.2485	43.55	141.81	7.80
19	SCC:6.0:30FA	-	23.50	22.50	8.31	0.2485	44.60	146.04	5.30
20	SCC:6.0:30FA	-	21.25	21.00	8.31	0.2485	44.60	146.04	6.60
21	SCC:6.0:30FA	-	22.00	20.00	8.31	0.2485	43.60	142.01	7.60
22	NC:6.0:30FA	3.50	-	-	8.31	0.2485	44.30	144.83	6.80
23	NC:6.0:30FA	4.00	-	-	8.31	0.2485	44.45	145.43	6.00
24	NC:6.0:30FA	3.75	-	-	8.31	0.2485	44.60	146.04	5.60
25	NC:6.0:30FA	3.00	-	-	8.31	0.2485	44.60	146.04	5.50

SCC with larger amounts of cementitious material and fly ash requires less HRWRA and more VMA as compared to SCC mixes without fly ash. Also, the SCC mix with 6 bag cementitious materials requires the use of less HRWRA.

3.1 Mixing Procedure

Once the mix design was determined, as outlined in Table 5, the next step was to create and mix the concrete. Representatives from NDDOT and Strata Corporation (SC) were present to guide trial batching on the first two days of mixing. The SC representatives aided the PI and UND personnel in establishing quality NC mixes and performing plastic state testing according to the proper specification. Bruce Docktor, PE from the Environmental and Energy Research Center at UND who maintains an ACI Level I Technician license, was present during all trial batching and testing. The mixing procedure follows ASTM C192 method. First, the coarse aggregate and three-fourths of the total amount of water, with the mid-range water reducing agent is placed in the 3 ft^3 mixing drum. The mixer is turned on to wet the rock; as the mixer turns, the total amount of fine aggregate, injected with AEA, is then added, along with the cementitious material. The remaining amount of water is used to wash material off of the mixer walls, and if needed, HRWRA or VMA is added. The concrete is mixed in a 3-,3-,2-minute interval pattern; in other words, it mixes for three minutes, rests for three minutes, and mixes another two minutes.

Once the concrete is completely mixed, the plastic state testing phase begins.

4.0 PLASTIC STATE TESTING

During the trial batching phase, ASTM standards developed specifically for SCC mixes and other traditional ASTM tests were used to evaluate the SCC mixes in the plastic state. The plastic state quality control tests for SCC mixes are listed in Table 10. All plastic property tests were performed immediately after mixing, and the slump flow retention curve was determined based on a period of forty-five minutes at fifteen minute intervals. It is worth noting that ASTM C143 and C138 will also be applied to NC mixes.

Table 10: Plastic state testing performed on SCC mixes

Plastic Property Tests		
Test Designation	Description	Target Value
ASTM C1611	Slump Flow, T_{20}, VSI	22-26"
ASTM C1621	Slump Flow w/J-Ring	within 2" of slump
ASTM C1610	Column Segregation	Less Than 10% mass difference
ASTM C138	Unit weight, air-content	141-145 pcf, 5-8%

4.1 ASTM C1611: Slump Flow of SCC

ASTM C1611, analogous to the conventional slump test for normal concrete (ASTM C143), provides a procedure to determine the slump flow of SCC. In addition, it monitors the consistency and flow potential of the fresh concrete, and measures filling ability and stability. The stability refers to the ability of a concrete mix to resist segregation of paste from aggregate (ASTM C1611). This test method involves the use of an Abrams cone (as specified in ASTM C143) that can be used in either the traditional position (large opening down) or inverted position (small opening down). The cone was placed in the center of a flat, level base plate made of non-absorbent, smooth, and rigid material. The spread board was free of standing water and had a minimum diameter of thirty-six inches. The cone mold is filled with SCC in one continuous lift without any rodding or consolidation, and lifted upward in one steady, continuous motion to a height of 230±75 mm (9±3 in) in two to four seconds [30]. Figure 9 displays the Abrams cone apparatus in use.

Figure 9: Abrams cone [31]

The concrete was allowed to flow onto the slump board and the spread was measured horizontally at its largest diameter. The diameter perpendicular to its largest diameter was also recorded to the nearest ¼”. If halo was observed it was included as part of the concrete diameter; halo is cement that has separated from the coarse aggregate and forms a ring around the outside circumference of the concrete after flowing from the cone. The slump flow was determined by averaging the two measured diameters; for SCC, the general slump value ranges between eighteen and thirty-two inches. Figure 10 shows the spread being measured in one direction.

Figure 10: Horizontal measurement of slump flow

A slump flow retention curve was carried out to forty-five minutes. A spread was measured immediately after mixing and after fifteen minute intervals. Just before measuring the spread at each interval, the concrete mixer spun the mix for two minutes to simulate field conditions. Table 11 summarizes the measured slump flow retention data for three SCC mixes, and Figure 11 shows the slump flow curve retention results for the same three mixes.

Table 11: Measured slump flow retention data

	Spread Flow Retention (inches) vs. Time elapsed, minutes				Admixtures Dosage (oz./cwt)			
Mix ID	0	15	30	45	Glenium PS 1466 (HRWR A)	Polyheed 1020 (WR)	Rheomac 450 (VMA)	MB AE 90 (AEA)
SCC:6.5:0.0FA	23	21.5	19	16	6	2	0	0.45
SCC:6.5:30FA	26	22	19.5	18	5	2	0.4	0.35
SCC:6.0:30FA	25.75	22	18	17	6	2	0	0.4

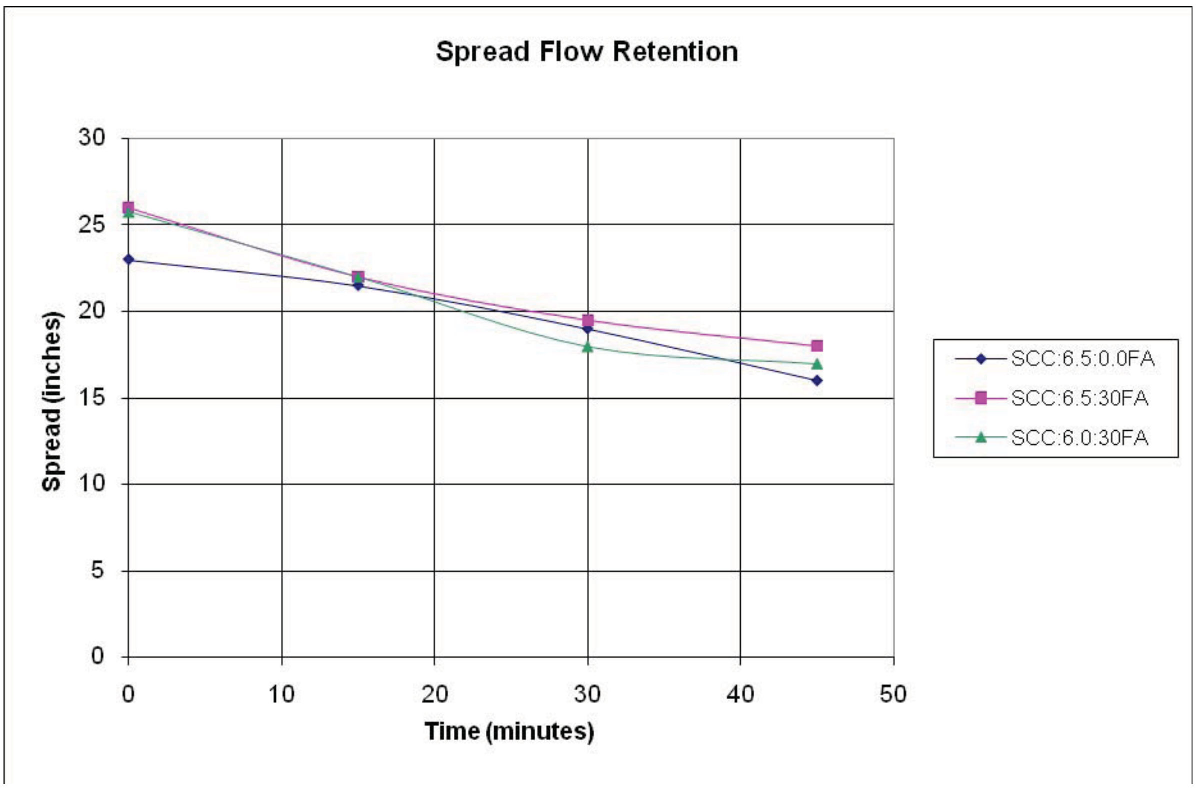


Figure 11: Slump flow retention for SCC mixes

Out of the three SCC mixes, SCC:6.5:30FA had the largest flow. This was expected because it had 611 pounds cementitious material with thirty percent fly ash, see Table 9 and Table 11. It is also observed that all three mixes tested for slump flow retention performed almost identically; the spread for each decreased linearly with time, see Figure 11.

Normal concrete mixes were tested according to ASTM C143, identical to ASTM

C1611 for slump flow of SCC except the NC mixes are consolidated prior to the test. Figure 12 shows a NC mix during the slump test. Typical values for slump of NC range between 3" and 4". Table 12 shows the average slump value of three NC mixes tested. See Table 9 for the complete list of slump values.

Figure 12: Slump of NC mixes varied between 3 inches and 4 inches, see Table 9 and Table 12.

Table 12: Slump for NC mixes

Mix ID	Slump (in)
NC:6.5:0.0FA	3.69
NC:6.5:30FA	3.31
NC:6.0:30FA	3.81

The Visual Stability Index (VSI) is another test used in combination with the slump flow test to examine the concrete mass during and after the cone is lifted. SCC was evaluated once it stops flowing and close attention was paid to the surface bleed, mortar halo, and aggregate distribution [30]. After evaluation, the mix was ranked in terms of the stability on a scale of 0-3, recorded to the nearest 0.5 increment, with 0 portraying a highly stable mix and 3 indicating an unacceptable mix. The VSI values and more specific criterion are outlined in Table 13.

Table 13: Visual Stability Index values (ASTM C1611)

VSI Value	Criteria
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	Slight mortar halo, less than 0.5" and/or aggregate pile in the center of the concrete mass.
3 = Highly Unstable	Clearly segregating by evidence of a large mortar halo (greater than 0.5") and/or a large aggregate pile in the center of the concrete mass

A more thorough explanation of these values is provided by the Nebraska Department of Roads, and is shown in Table 14.

Table 14: VSI descriptions from the Nebraska Department of Roads [20]

VSI	Description of quality
0	High quality SCC with no indication of segregation or separation. Very good aggregate distribution and materials carried to the outer edge of the slump flow
1	High quality SCC, mix is starting to exhibit a mortar halo and possibly some bleed water/separation. This is an acceptable SCC mixture. Good aggregate distribution, although a little more mortar is present at the outer edges of the slump flow
2	Mix is exhibiting more mix separation, a more pronounced mortar halo, and uneven distribution of aggregate. Quality Control (QC) personnel should evaluate this mix further beforec acceptance or rejection. Retest from another sample.
3	Mix showing all signs of segregation, separation, bleeding, and instability. Reject this mix.

Figure 13, Figure 14, and Figure 15 display pictures of three SCC mixes from this research project with different VSI values.   Figure 13 shows a SCC mix with VSI equal to 0, while Figure 14 shows a SCC mix with VSI of 0.5, and Figure 15 shows a mix with VSI of 2.

Figure 13: SCC mix with VSI=0

Figure 14: SCC mix with VSI=0.5, evidence of bleeding in the center

Figure 15: SCC mix with VSI=2 [16]

As the VSI increases, the SCC mixes show more evidence of bleeding. Any mixes created during the trial batching phase of this research project with a VSI of 1 or greater was thrown out.

Figure 16 shows a mix with high viscosity, yielding a spread of eighteen inches, which is below the project parameters.

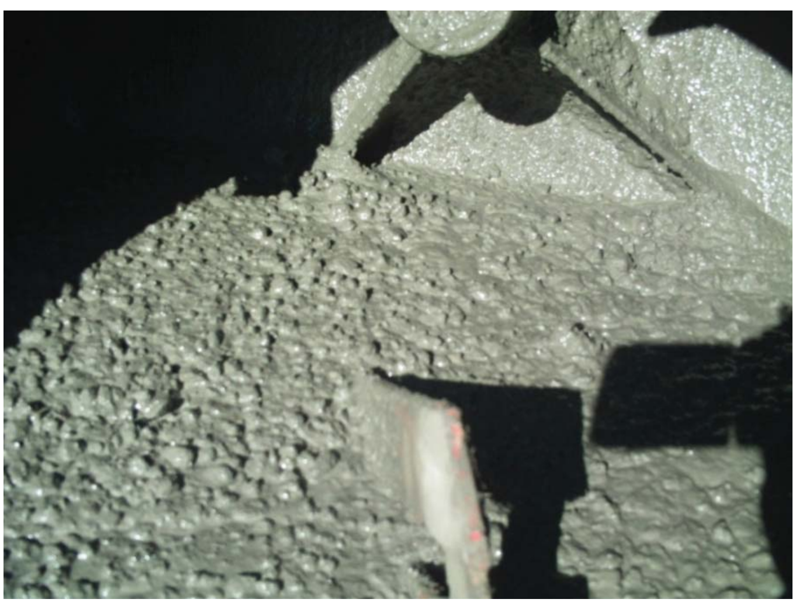


Figure 16: Very viscous SCC mix

Figure 17 shows of a batch of SCC:6.5:0.0FA with a slight amount of bleed water but was still satisfactory.

Figure 17: SCC:6.5:0.0:FA just prior to the spread

Figure 18 depicts the spread of a typical SCC:6.5:30FA bath with VSI=0.

Figure 18: Spread of SCC:6.5:30FA with VSI=0, ideal spread

The T_{20} test, also performed in accordance with ASTM C1611, evaluates the time it takes for the spread to reach twenty inches (T_{20}) and provides a relative measure of the plastic viscosity of the SCC. The test procedure was carried out with the same apparatus as the slump flow test. However, on the slump flow board, a twenty inch diameter circle was outlined. The Abram's cone was filled with SCC in one lift and a stopwatch was started as soon the Abram's cone is lifted. The time it took for the fresh concrete to expand into the twenty inch diameter circle was recorded to the nearest 0.1 second. Typically, the T_{20} values range from two to five seconds. A higher value reveals a more viscous SCC mix and suggests it be used for concrete with congested reinforcement or in deep sections [32]. On the other hand, a lower value depicts a less viscous mix that is more feasible for concrete traveling long horizontal distances.

4.2 ASTM C1621: Slump Flow with J-Ring

The purpose of the J-Ring test is to measure the passing ability of SCC in densely reinforced concrete members. The test is limited to concrete with a maximum aggregate size of one inch and is performed similarly to the slump flow test. The difference is that a rigid ring of reinforcing bar is placed around the inverted slump cone. The dimensions of the ring are specified in ASTM C1621 and are given in Table 15. The J-Ring apparatus and its dimensions A, B, C, D, E, and F are shown in Figure 19. The concrete was placed in one lift without vibration in the same slump mold, concentric with the J-ring. The mold was raised in one continuous upward motion and the concrete was allowed to pass through the J-ring. The diameter of the concrete spread was again measured in two directions and averaged to determine the J-ring flow; the difference between the slump flow with and without J-Ring determined passing ability, and for this research project it was decided that it should not differ by more than two inches. Just as in the slump flow test, the VBI was rated. ASTM C1621 provides a VBI rating table within the specification, see Table 16.

Table 15: J-Ring dimensions

Dimension	in.	mm.
A	12±0.13	300±3.3
B	1.5±0.06	38±1.5
C	0.625±0.13	16±3.3
D	2.36±0.06	58.9±1.5
E	1.0±0.06	25±1.5
F	4.0±0.06	100±1.5

Table 16: Blocking Assessment; VBI Rating (ASTM C1621)

Difference Between Slump Flow With and Without J-Ring	VBI rating
0 to 1 in.	No visible Blocking
> 1 to 2 in.	Minimal to noticeable blocking
> 2 in.	Noticeable to extreme Blocking

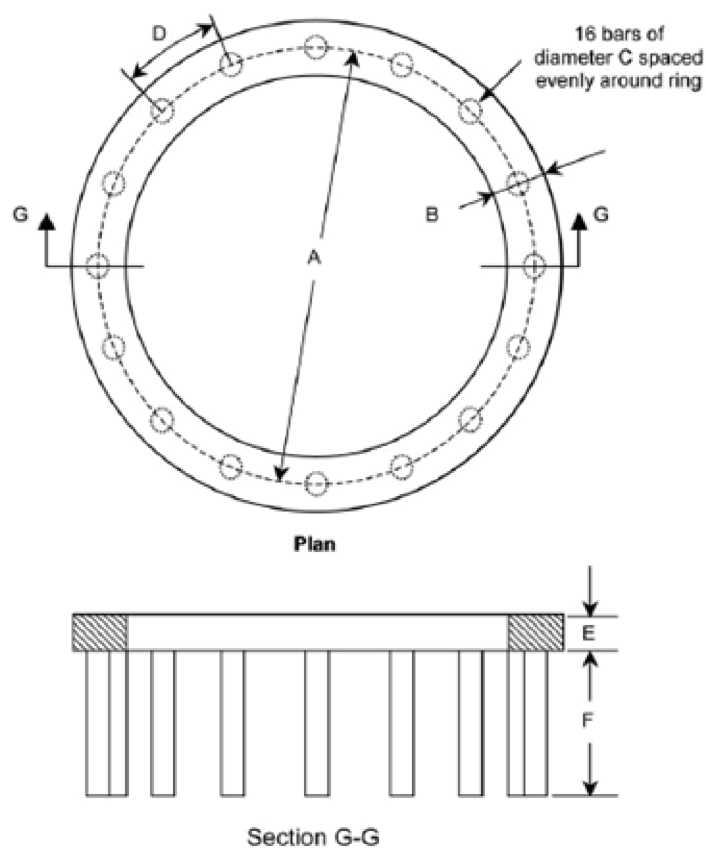


Figure 19: J-Ring Apparatus dimensions (ASTM C1621)

Figure 20 shows a typical slump flow with J-Ring and VBI=0, while slump flow with J-Ring and VBI=3 is illustrated in Figure 21. This mix shown in Figure 21 is thrown out because the VBI exceeds the maximum limit for acceptable performance.

Figure 20: Typical J-Ring with VBI=0

Figure 21: Slump flow with J-Ring VBI = 3.

Figure 22: SCC:6.5:30FA. 24 inches

Table 17 displays the average spread of three SCC mixes using the J-Ring. See Table 9 for the entire J-Ring results.

Table 17: J-Ring Results

Mix ID	J-Ring (in)
SCC:6.5:0.0FA	22.25
SCC:6.5:30FA	22.25
SCC:6.0:30FA	21.56

Results from the J-Ring test show that for 6.5 bags of cementitious material, addition of fly ash does not alter the spread through the J-Ring. SCC:6.5:0.0FA and SCC:6.5:30FA both had average spreads of 22.25 inches, see Table 17. SCC with only 6 bags of cementitious material, however, had lower spreads; SCC:6.0:30FA spread 21.56 inches, see Table 17.

Evaluation of the mixes during the mixing process helps determine its characteristics. For instance, one way to judge the mix is to stop the mixer and observe how the mix settles at the bottom of the mixer. The mix should appear to have slight ripples in its surface (rocks just at the top surface). Another observation was a slight layer (1/4”) of mortar at the top of the mixer. When this occurred, it resulted in a mix with a visual blocking index (VBI) of 0.5 – 1.0. While this VBI is at the upper limit in this project, the mix was still acceptable. The

VBI was used in addition to VSI when deciding whether or not to cast specimens from a trial batch. Typically if the VSI was not 0 or 0.5, the mix had problems with air-content. For any SCC mix cast in this project, the largest VSI and VBI was 0.5.

Another quality to observe in the mixer was if the mix had a "sheen" in the light and if it was "rolling off" of the mixer paddles, as shown in Figure 23.

Figure 23: SCC rolling in the mixer

Instability, in all cases occurred when too much HRWRA was dispensed into the mix before observing the stationary mix. For the given aggregate gradation and water content a stable spread of up to twenty-three inches could be reached with no VMA. Any spread beyond twenty-three inches would require VMA to hold it together. HRWRA dosages were mostly 2.8 -5.2 oz/cwt with the exception of one case where 9 oz/cwt was used for SCC:6.5:0.0FA; dosages of VMA were 0.30 oz/cwt or less, see Table 5. Observations show that fly ash improved the flowability of the mix, see Table 6; therefore it is recommended that it be used whenever possible in SCC mixes.

4.3 ASTM C1610: Column Segregation

The column segregation test was used to measure the static stability of SCC by quantifying aggregate segregation. Due to the time required to perform the ASTM C1610 test, use of the column segregation test in the field is not practical; however, the test is feasible when qualifying mixes in the trial batch phase. The procedure, as specified by ASTM C1610, involved filling an eight inch diameter poly-vinyl chloride pipe with SCC in one continuous lift. A schematic of the apparatus is displayed in Figure 24. Top and bottom sections are thirteen inches in height and the middle section has a height of twenty-six inches. After placement and allowing the mix to sit for fifteen minutes, the column was separated into three sections. Figure 25 depicts how the column in this research program was separated. The top section was removed and the mix was washed over a No. 4 sieve to remove all of the mortar, as shown in Figure 26. The rock was then brought to a saturated surface dry condition and weighed. The middle section was thrown out and the process was repeated on the bottom section. The weights of both the top and bottom sections of the column were compared to determine if the mix segregated. In other words, a consistent aggregate mass in each section denotes a non-segregating mix, while a segregating mix has higher aggregate concentrations in the lower section.

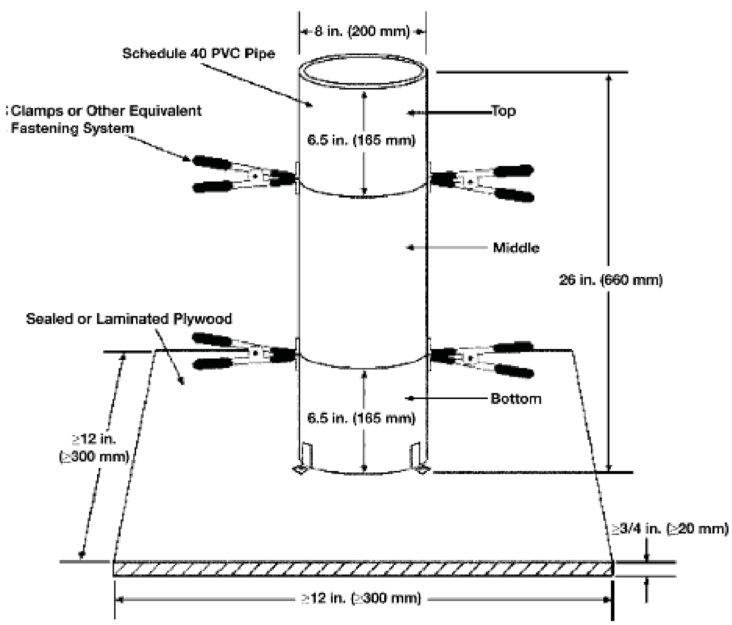


Figure 24: Dimensions of column segregation apparatus

Figure 25: Column Segregation apparatus

Figure 26: Aggregate washed over No. 4 sieve from the column segregation apparatus

Three mixes, SCC:6.5:0.0FA, SCC:6.5:50FA, and SCC:6.0:30FA were utilized in the column segregation test. Equation 2 was used to determine the static segregation percentage for each mix.

$$S = \frac{(CA_B - CA_T)}{(CA_B + CA_T)} \times 100 \quad if \quad CA_B > CA_T$$
$$S = 0 \quad if \quad CA_B \leq CA_T \tag{2}$$

where:

S = Static segregation, %

CA_B = Weight of coarse aggregate in bottom section, lbs

CA_T = Weight of coarse aggregate in top section, lbs

For the SCC:6.5:0.0:FA mix, eleven pounds of aggregate from the top section and 12.35 pounds of aggregate from the bottom section were retained on the No. 4 sieve; equation 2 was used to calculate a static segregation of 5.78%. The SCC:6.5:30FA mix retained 10.95 pounds of aggregate from the top section and 12.05 pounds of aggregate from the bottom section, resulting in a static segregation of 4.78%. Finally, the third mix, with 10.7 pounds of aggregate from the top section and 11.6 pounds of aggregate from the bottom section, had a static segregation of 4.04%. In all three mixes, the aggregate weights from the top and bottom sections were very similar. Also, these results, shown in Table 18, clearly show that the static segregation never exceeded six percent by weight for any of the mixes. Adequate consolidation was therefore achieved and the mixes were not segregating.

Table 18: Static Segregation results for SCC mixes

Mix ID	Mass retained Top, lbs	Mass retained, bottom, lbs	% Static Segregation
SCC:6.5:0.0FA	11	12.35	5.78%
SCC:6.5:30FA	10.95	12.05	4.78%
SCC:6.0:30FA	10.7	11.6	4.04%

4.4 ASTM C138: Unit Weight and Air Content

ASTM C138 is used during plastic state testing to determine the density, or unit weight, of the freshly mixed concrete, as well as yield, cement content, and air content. Yield is the "volume of concrete produced from a mixture of known quantities of the component materials." This research project utilized part of this test procedure since unit weight and air content were the desired parameters. This testing procedure involves the use of a balance accurate to 0.1 lb or to within 0.3% of the test load and a measure, which is a cylindrical steel container. The balance was used to determine the weight of the empty measure and then the freshly mixed concrete was placed in the measure. Since the measure cannot contain an excess (protrusion of ⅛ inch above the top) or deficiency of concrete, concrete was added or removed, depending on the mix trial to satisfy these requirements. A strike-off plate, a flat rectangle metal plate at least ¼ inch thick and at least two inches wide and long, was used to strike-off the top surface of concrete and provide a smooth finish. This was done by pressing the plate on the top surface of the measure to cover about two thirds of the surface and removing it with a sawing motion to finish the original area covered. Then the plate was placed on the top of the measure to cover the original two thirds of the surface, a vertical pressure was applied, and a sawing motion was used again to cover the whole surface of the measure. This motion was continued until it slid off the measure. Upon completion, all excess concrete was cleaned from the measure and the balance was used to determine the weight of the measure and concrete. The density of the concrete was determined by equation 3:

$$D = \frac{M_c - M_m}{V_m} \qquad (3)$$

D = density, lb/ft^3

M_c = Mass of the measure filled with concrete, lb,

M_m = Mass of the measure, lb, and

V_m = volume of the measure, ft^3.

The air content of the concrete is then determined by equation 4:

$$A = \frac{T - D}{T} \times 100$$

where:

A = Air content, % (4)

T = Maximum theoretical weight, lb/ft^3, and

D = density (unit weight), lb/ft^3.

Table 19 lists the average unit weight and air content of three SCC mixes. See Table 9 for specific trial results. The air content for all SCC mixes varies within the acceptable range of 5 to 6 %, see Table 19.

Table 19: Unit Weight and Air Content of SCC mixes

Mix ID	Unit Wt (pcf)	Air Content %
SCC:6.5:0.0FA	143.0645161	5.9
SCC:6.5:30FA	144.6774194	5.5
SCC:6.0:30FA	146.2903226	5

5.0 HARDENED PROPERTY TESTING

Following the completion of the plastic state testing, the concrete was poured into specimens, and placed in order to prepare the samples for the hardened state testing.

A thorough investigation of the hardened samples is necessary in order to examine tensile, compressive, shear, and bond strength. In addition, permeability, modulus of elasticity, hardened air-content (air void structure analysis), and shrinkage must also be evaluated in order to reach conclusions about the SCC behavior. Table 20 lists all hardened property tests performed in this project. It lists the test's ASTM designation, test description, specimen size, number of specimens per mix, test age, and the total number of specimens needed for each test.

Table 20: Hardened property tests

ASTM Designation	Description	Specimen Size	Number of specimens per mix	Test Age (days)	Total number of specimens
C39-04	Compressive Strength	4x8" cylinder	3	1,7,28,56	72
C293-02	Modulus of Rupture	6x6x18" beam	3	28	18
C469-02	Modulus of Elasticity	6x12" cylinder	3	28	18
C157-04	Drying Shrinkage	4x4x11.25" beam	3	28	18
C1202-97	Chloride-ion permeability	4"x2" disc	3	28	18
C457-98	Linear Traverse	4x8" cylinder	1	28	6
C496-04	Splitting Tensile Test	6x12" cylinder	3	28	18
A944-04	Bond Strength	24"x15.5"x9.5"	3	28	18

Most of the tests listed are conventional, but ASTM A944 is a unique test that gives a comparison bond value for different types of concrete.

5.1 ASTM C39-04: Compressive Strength

Compressive strength of concrete depends on the size and shape of the aggregate, as well as the age of the specimens, batching, mixing, molding, and curing conditions. To test for compressive strength, moist-cured specimens were placed in between upper and lower bearing blocks on the testing machine. The load indicator was set to zero and a compressive axial load was applied continuously until the load indicator showed that the load was decreasing slowly and the specimen showed evidence of fracture. The maximum load attained was recorded and divided by the cross sectional area of the specimen to determine compressive strength.

The results of this test method are used as a basis for quality control of concrete proportioning, mixing, and placing operations, and for determination of compliance with specifications control for evaluating effectiveness of admixture and similar uses.

The strength gain of each mix design versus age of the design samples is shown in

Figure 27. A total of twelve specimens per mix design were tested and each point on the graph represents the average of three tests performed on each mix and a test age in accordance with ASTM C39-049. As expected, the mixes gained seventy percent of their strength within the first seven days, see Figure 27.

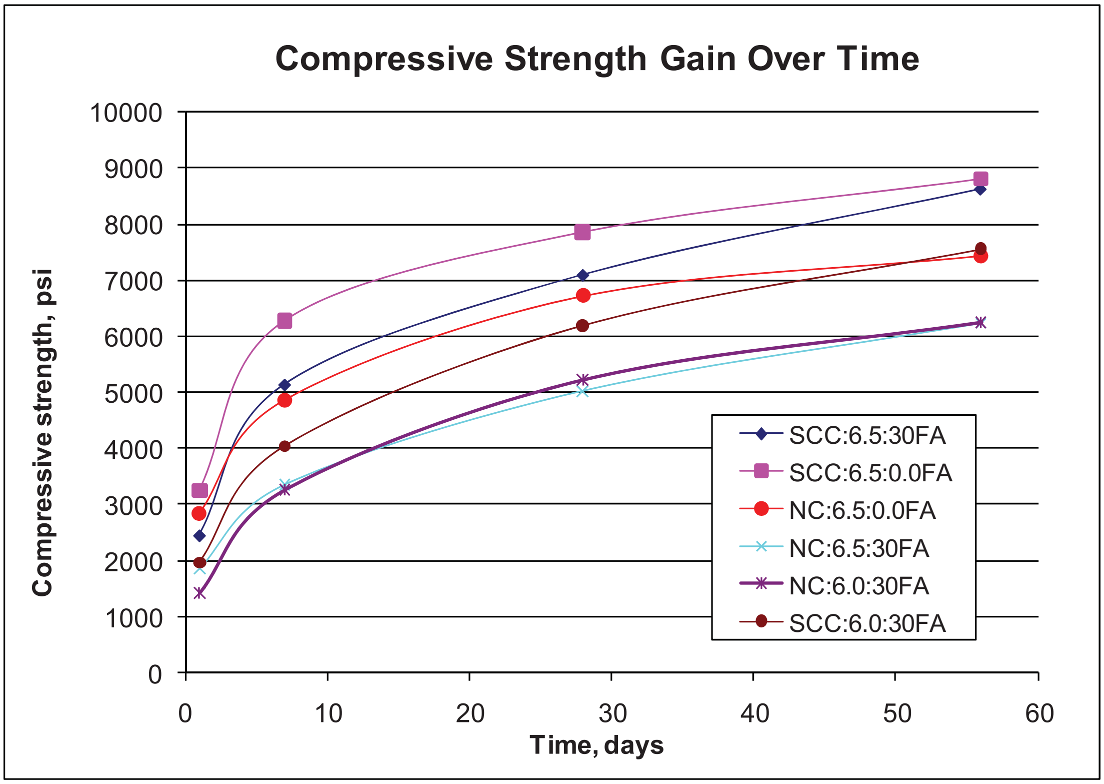


Figure 27: Compressive strength gain vs. time for all 6 mix designs

The results in Figure 27 indicate that SCC mixes exhibit higher and faster strength gain as compared to the NC counterpart mixes. SCC mixes, on average, have ten to twenty percent greater compressive strength, as compared to their NC counterparts, for a given age and cementitious material content. For example, compare SCC:6.5:0.0FA with NC:6.5:0.0FA, see Figure 28. Also, compare SCC:6.5:30FA with NC:6.5:30FA, see Figure 29, and compare SCC:6.0:30FA with NC:6.0:30FA, see Figure 30.

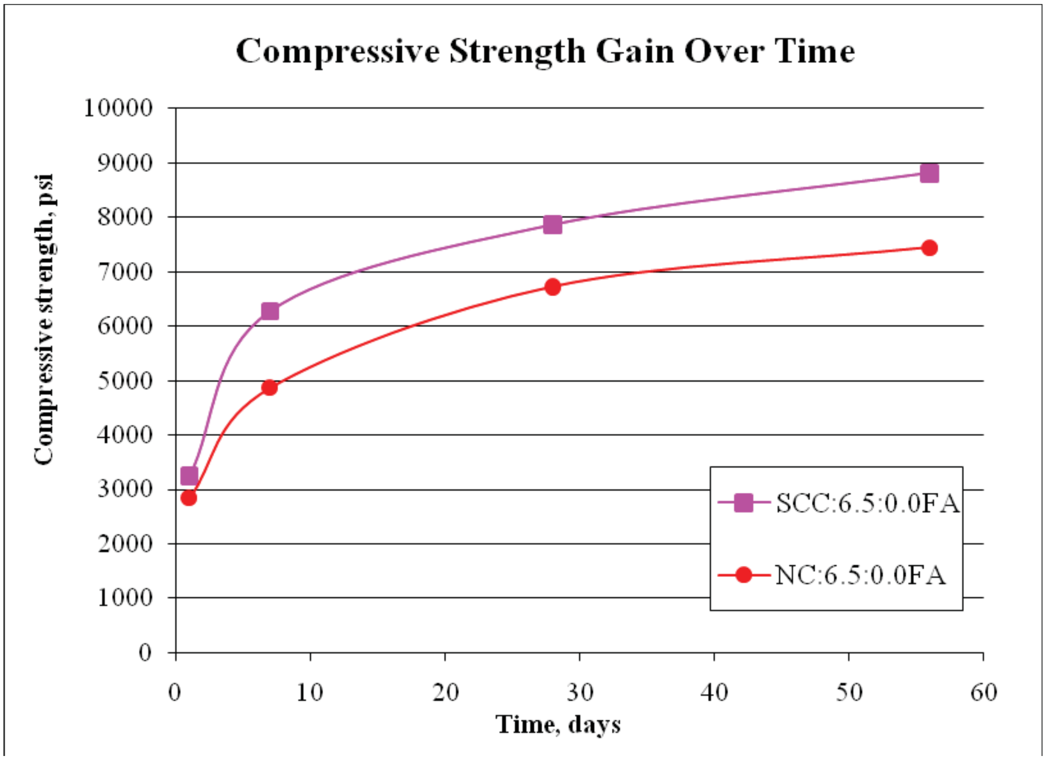


Figure 28: Compressive Strength of SCC:6.5:0.0FA vs. NC:6.5:0.0FA

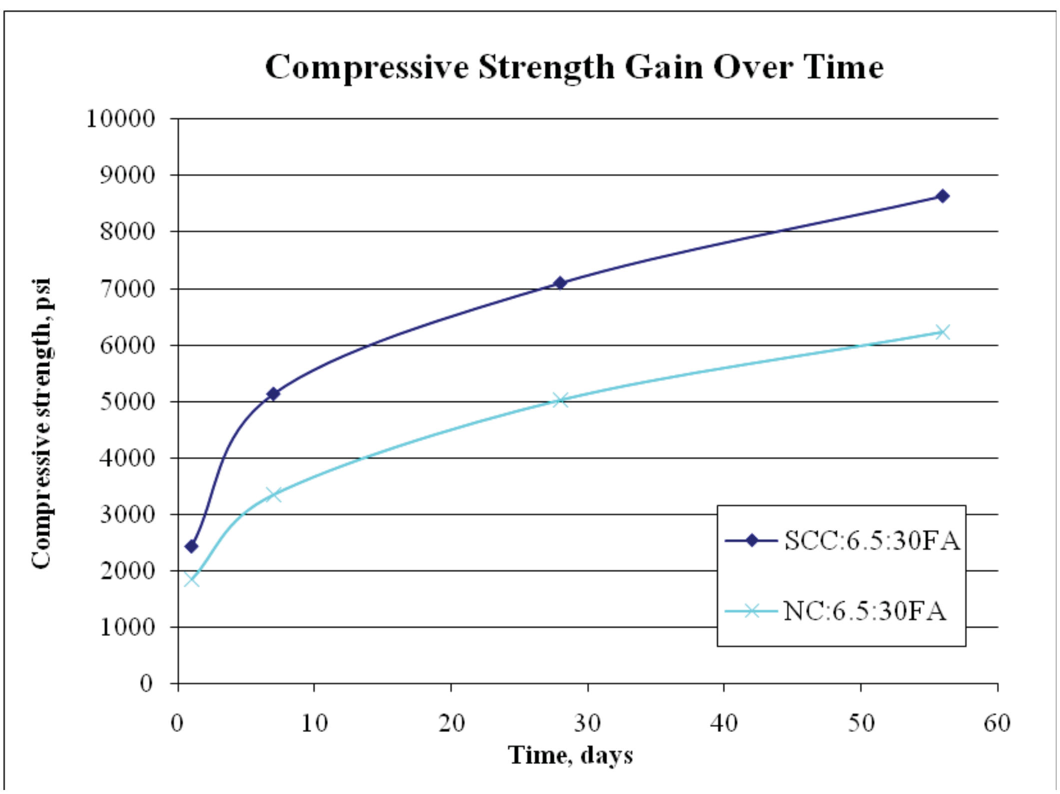


Figure 29: Compressive Strength of SCC:6.5:30FA vs. NC:6.5:30FA

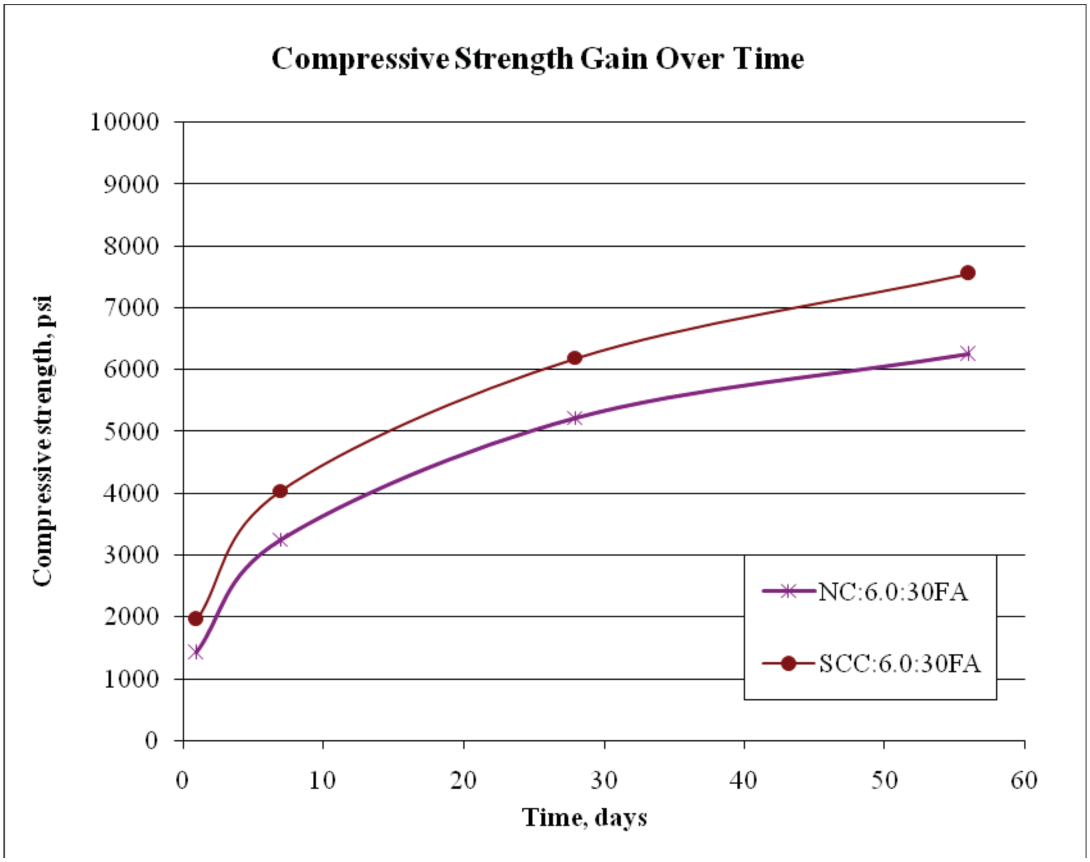


Figure 30: Compressive Strength of NC:6.0:30FA vs. SCC:6.0:30FA

In addition, mixes with fly ash had lowered and delayed compressive strength gain. For example, compare SCC:6.5:30FA with SCC:6.5:0.0FA, see Figure 31, and compare NC:6.5:30FA with NC:6.5:0.0FA, see Figure 32.

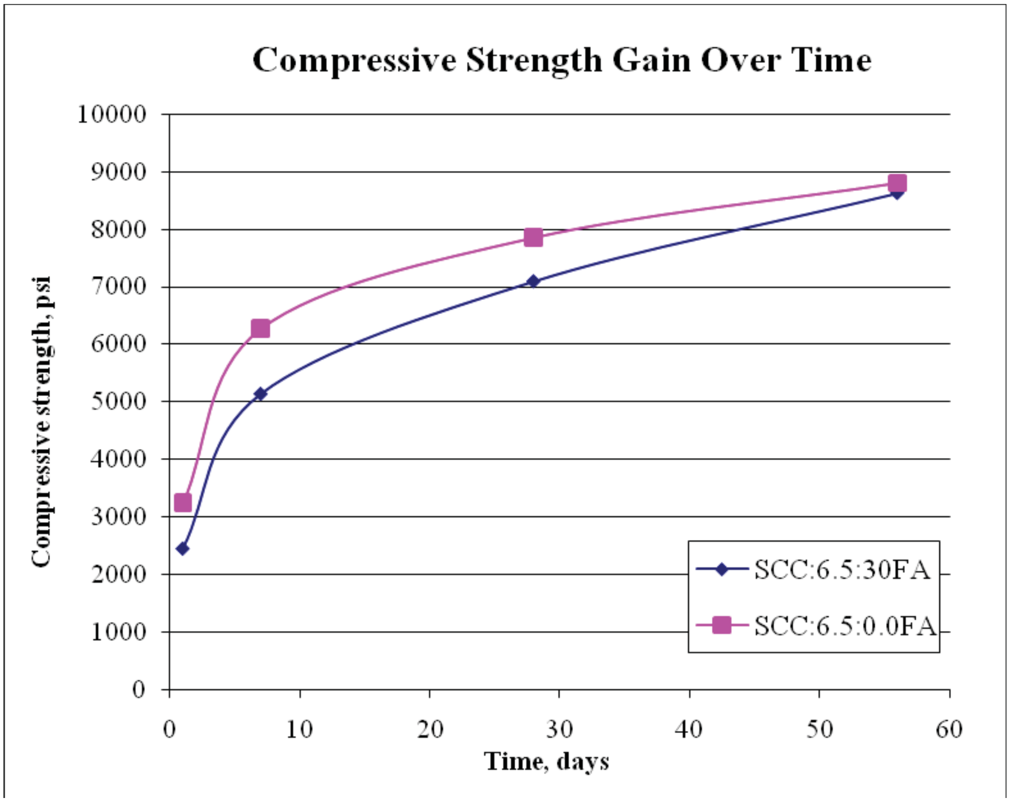


Figure 31: Compressive Strength of SCC:6.5:30FA vs. SCC:6.5:0.0FA

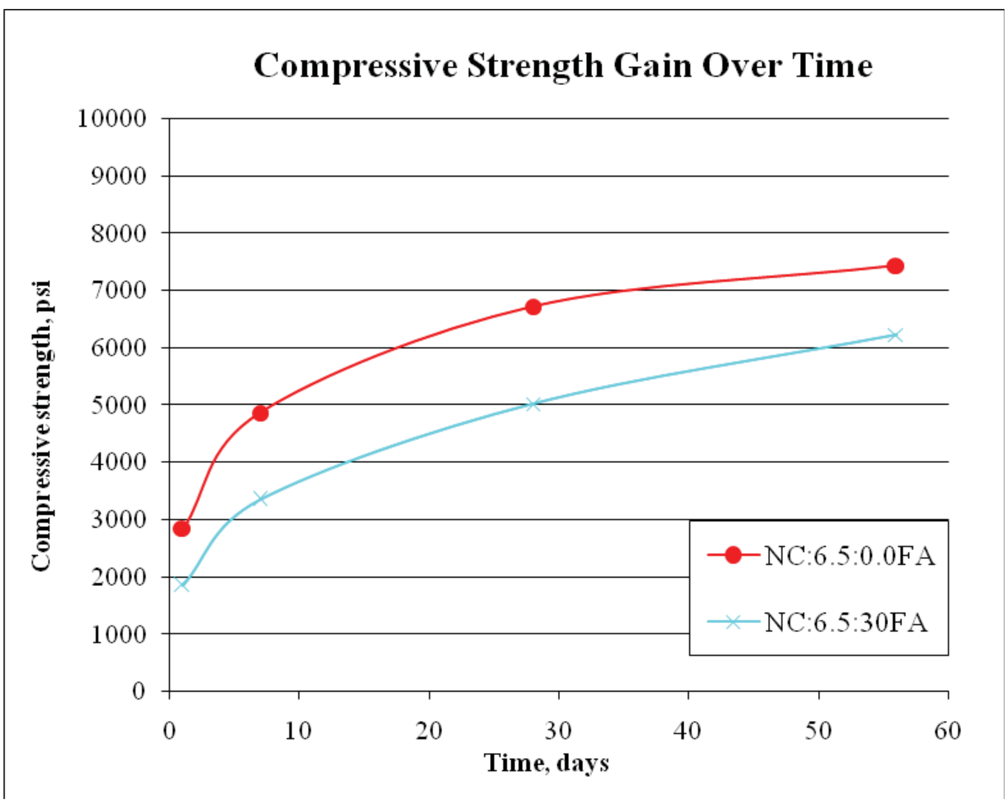


Figure 32: Compressive Strength of NC:6.5:0.0FA vs. NC:6.5:30FA

The NC mix containing fly ash with 6 bags of cementitious material (NC:6.0:30FA) performed almost the same as the NC containing fly ash with 6.5 bags of cementitious material (NC:6.5:30FA), see Figure 33. The SCC mix with 6.5 bags of cementitious material containing fly ash outperformed the SCC mix with 6 bags of cementitious material containing fly ash (compare SCC:6.5:30FA with SCC:6.0:30FA, see Figure 34).

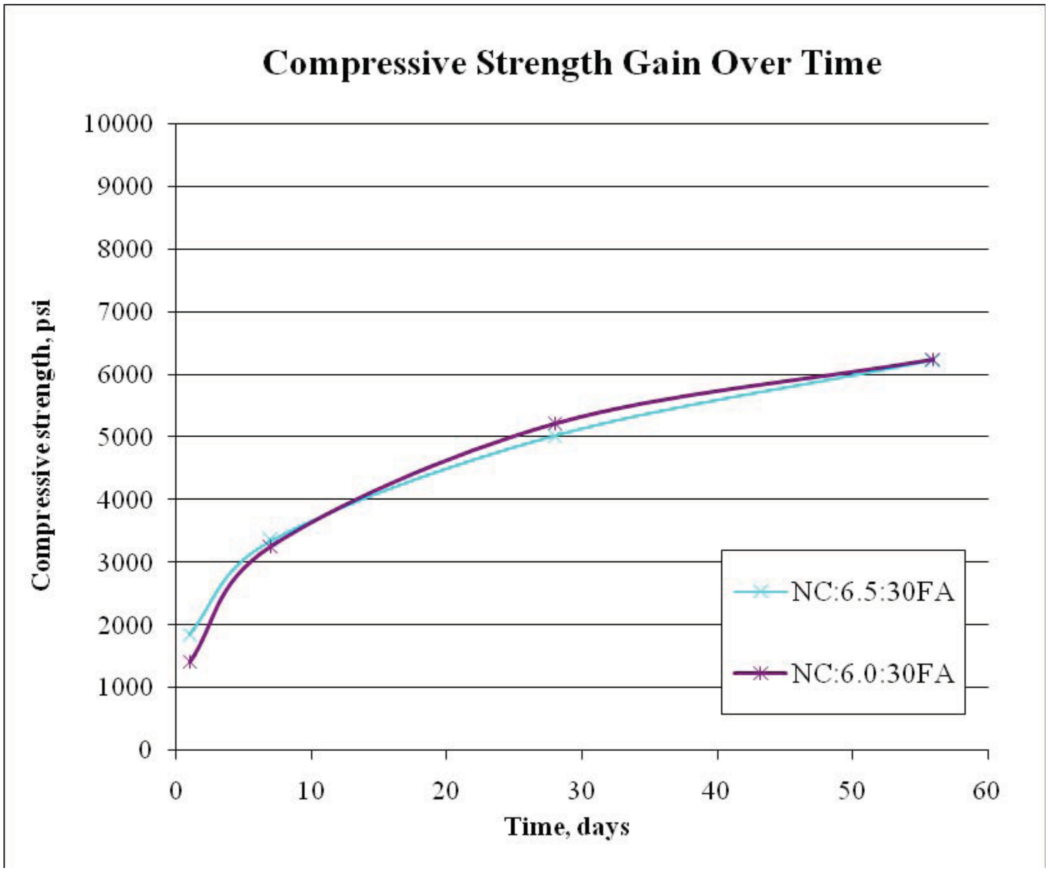


Figure 33: Compressive Strength of NC:6.5:30FA vs. NC:6.0:30FA

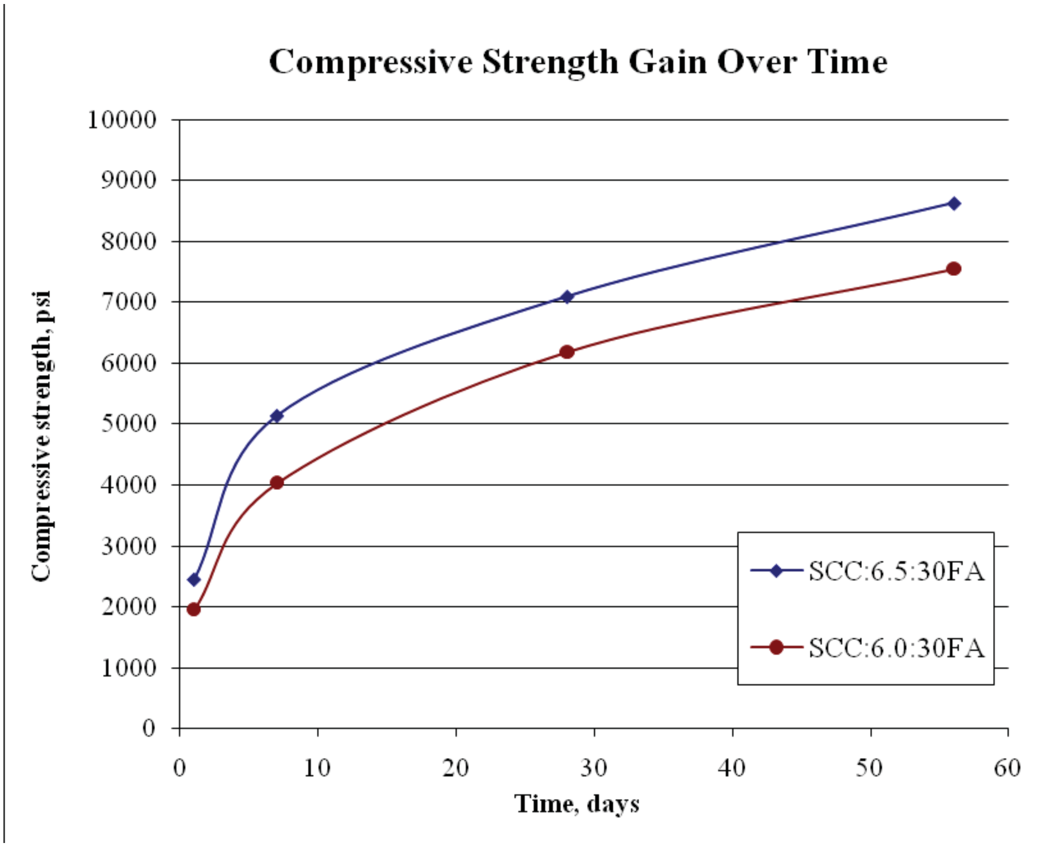


Figure 34: Compressive Strength of SCC:6.5:30FA vs. SCC:6.0:30FA

These results imply that SCC with higher cementitious material exhibits higher compressive strength. SCC with 6.5 bags of cementitious material without fly ash (SCC:6.5:0.0FA) outperformed all mixes tested with regards to strength gain, especially at the age of seven days and twenty-eight days. However, the strength gain for the SCC counterpart with fly ash is almost the same at the age of fifty-six days (compare SCC:6.5:0.0FA with SCC:6.5:30FA), see Figure 31. A SCC mix that contains less cementitious material than a comparable conventional (NC) mix exhibits more strength. SCC:6.0:30FA outperformed and had greater strength than all NC mixes at fifty-six days, see Figures 27 and 30. Comparing SCC:6.5:0.0FA and SCC:6.5:30FA, two SCC mixes with equal number of cement bags, results in the conclusion that altering the amount of fly ash does not affect compressive strength at fifty-six days, see Figure 31. From these results, it is concluded that higher cementititous material is beneficial for SCC mixes, see Figure 34, while the increase in cementitious material has insignificant effect on strength gain of NC, see Figure 33.

Since all mixes had identical aggregate proportions and water-cement ratios, these results indicate SCC has comparable strength gain to its NC counterpart. The compressive strength test results indicate that SCC outperforms its NC counterpart. In summary, the following conclusions can be reached from compressive strength test. First, fly ash has the effect of lowering and delaying compressive strength gain. In addition, SCC mixes have ten to twenty percent greater compressive strength as compared to their NC counterparts. Furthermore, higher amounts of cementitious material result in larger compressive strengths for SCC mixes, while increasing cementitious material has an insignificant effect on compressive strength gain for NC mixes. Finally, compressive strength test results indicate that SCC outperforms its NC counterparts.

5.2 ASTM C293-02: Modulus of Rupture

The modulus of rupture (MOR) test is used to determine the MOR (or flexural strength) of concrete specimens by use of center point loading in accordance with ASTM C293-02. Eighteen 6”x6”x18” beams (three specimens per mix design) were used in this test. The moist cured specimens were removed from moist storage and tested for flexural strength as soon as possible; surface drying on the specimens can lead to a reduced modulus of rupture. The specimens were placed on support blocks of the testing machine, see Figure 35. The load-applying block was placed in contact with the specimen at the center and a constant load of three percent of the ultimate load was applied. In order to determine if gaps exist between the specimen and the load-applying or support blocks, gages of 0.004 inches and 0.015 inches were used. The specimens were ground to eliminate gaps greater than 0.004 inches. Grinding was only used when gaps exceed 0.015 inches. The load was applied constantly and without shock until it reached breaking point so the extreme fiber stress increased at a rate of 125 to 175 psi/min. Figure 35 shows the MOR test setup used in this research.

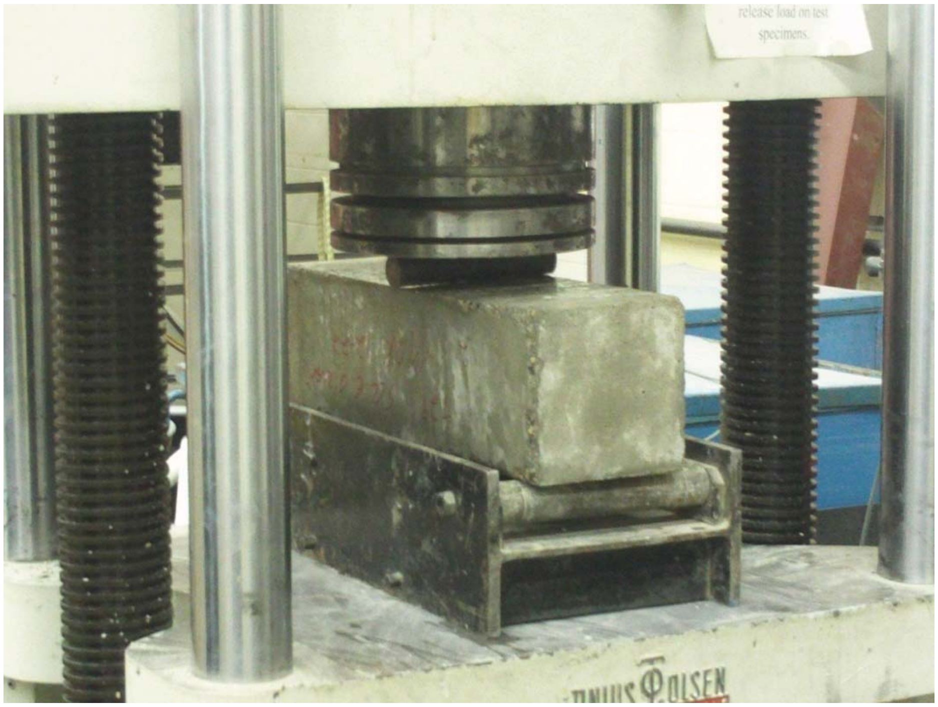


Figure 35: Apparatus used to perform ASTM C293-02

Once the breaking point is reached, the dimensions of the fracture faces were determined in order to calculate MOR. One measurement was taken at each edge of the fracture surface and one at the center. Three measurements in each direction are needed to obtain the average width and depth at fracture. MOR was then calculated by the following equation:

$$MOR = \frac{3PL}{2bd^2}, \quad psi \tag{5}$$

where:

MOR = modulus of rupture, psi,

P = maximum applied load, lbf,

L = span length, in,

b = average width of specimen at fracture, in, and

d = average depth of the specimen at fracture, in.

The modulus of rupture was tested the same day as the compressive strength (28 days) so a comparison can be made to ACI 318-08 Section 9.5.2.3, Equation 9-10:

$$\alpha = \frac{MOR}{\sqrt{f_c'}} \qquad (6)$$

where:

α = coefficient of *MOR* = 7.5

$\sqrt{f_c'}$ = Compressive strength of concrete at 28 days, psi.

Table 21 lists the results of MOR for each mix design. The coefficient of MOR is calculated by dividing the measured MOR by the square root of the specimen's actual compressive strength. The test results show that the coefficient for MOR is between eleven and twelve, indicating excellent tensile strength and aggregate interlock. The modulus of rupture test results indicate that the SCC mixes performed well as compared with the NC mixes, see Table 21.

Table 21: Modulus of rupture results at 28 days.

Mix ID	fc' (psi)	MOR (psi)	α=√fc'
SCC:6.5:0.0FA	7858	1065.12	12.02
NC:6.5:0.0FA	6721	910.99	11.11
SCC:6.5:30FA	7568	861.90	9.91
NC:6.5:30FA	5027	854.25	12.05
SCC:6.0:30FA	6194	882.19	11.21
NC:6.0:30FA	5228	875.54	12.11

5.3 ASTM C469-02: Modulus of Elasticity

The modulus of elasticity (MOE) of the concrete specimens was found by the test procedure outlined in ASTM C469-02. Moist-cured specimens were placed between the upper and lower bearing blocks of a compressometer with a digital dial gage attached that allowed deflections to be recorded at each load step, see Figure 36. Each specimen was weighed prior to loading and the unit weight was calculated; then the specimen was loaded to forty percent of its failure load to ensure that the loading only occurred in the elastic range. Dial gage readings were taken at intervals of 10,000 lbs up to 80,000 lbs and then the load was released. The specimen was reloaded to failure to obtain the 28 day compressive strength.

Figure 36: Modulus of Elasticity testing assembly

A CDI brand dial gage was used to measure deflection of the compressometer after each test. Deflections were measured on three specimens per mix design and their respective MOE calculated from a best fit line that described the linear elastic deformation. The MOE is found by the equation:

$$E = \frac{S_2 - S_1}{\varepsilon_2 - 0.00005} \tag{7}$$

where:

E = Modulus of elasticity

S_2 = stress at 40% of load, psi

S_1 = stress relative to 50 millionths strain, psi, and

ε_2 = longitudinal strain produced by S_2.

Since the unit weight and compressive strength were measured for each specimen, the results were compared to the ACI equation for MOE:

$$E_c = w_c^{1.5} 33\sqrt{f'_c} \quad (ACI\ 318-08,\ Section\ 8.5.1) \tag{8}$$

where:

w_c = unit weight, lb/ft^3.

$\sqrt{f_{c'}}$= compressive strength at 28 days, psi.

The MOE of each mix design determined by testing and the comparative value calculated by the ACI equations are listed in Table 22. The percent difference between the measured MOE and calculated MOE is calculated by equation 9 to illustrate how well equation 8 predicts values for NC and SCC mixes.

$$Percent\ Difference = \frac{\text{Average of Measured } MOE - \text{Average of ACI Calculated } MOE}{\text{Average of Measured } MOE} \tag{9}$$

Table 22: Modulus of elasticity results

Specimen ID	Average Measured MOE, ksi	Avg. ACI Calculated MOE, ksi	% difference
SCC:6.5:0.0FA	5174.57	5142.80	0.62%
NC:6.5:0.0FA	4827.29	4332.53	11.42%
SCC:6.5:30FA	4873.49	4560.01	6.87%
NC:6.5:30FA	5045.05	4120.39	22.44%
SCC:6.0:30FA	5257.77	4413.66	19.12%
NC:6.0:30FA	4442.94	4313.81	2.99%

The modulus of elasticity for the SCC mixes is higher than that of the NC mix counterpart, see Table 22.

The results indicate that all mixes had greater stiffness than those calculated by the ACI 318 equation. Since MOE is dependent on the aggregate type, coarse aggregate content, and compressive strength, these results show that SCC mixes would have comparable stiffness to the counterpart NC mixes.

In summary, the modulus of elasticity for SCC mixes outperforms that of the NC mixes. Also, for all mixes tested in this project, the measured MOE was exceeds the calculated MOE by the ACI 318 equation.

5.4 ASTM C157-04: Drying Shrinkage

ASTM C157-04 tests shrinkage of concrete specimens over a given period of time by measuring length change under a constant environment (fifty percent relative humidity and 73 degrees Fahrenheit). Measurement of length change permits assessment of the potential for volumetric expansion or contraction of SCC and NC mixes. This test method is particularly useful for comparative evaluation of this potential in different SCC and NC mixtures. The concrete was mixed and molded in accordance with ASTM C192, and the specimens, prisms with a 4 inch cross section (4” x 4”) and 11 ¼ inches long, were cured in the molds under moist conditions. Stainless steel studs were embedded at the ends of each specimen to provide a reference point when measuring length. Figure 37 shows an image of a length change specimen used in this research program.

Figure 37: Length change specimen.

Twenty-four hours after the addition of cement and water during mixing, the specimens were removed from the molds and placed in a limewater bath for thirty minutes. Once removed, the initial comparator reading was taken. The specimens were then submerged in lime water for twenty-eight days; following this bath, specimen lengths were recorded as the second comparator reading. They were then moved into a constant environment chamber for 16 weeks (112 days). Readings were taken after 56 days and 112 days. The percent length change was calculated by:

$$\Delta L_x = \frac{CRD - initial\ CRD}{G} \times 100 \tag{10}$$

where:

ΔL_x = length change of specimen at any age, %,

CRD = difference between comparator reading of specimen and reference bar at any age, and

G = The gage length, 10 in.

Results for each mix design are summarized in Table 23, with each reported value representing the average of three specimens per mix design.

Table 23: Length change results for 28, 56, and 112 days.

Mix ID	Average % Length Change at 28 days	Avg. Length change at 56 days (%)	Avg. Length change at 112 days (%)
NC:6.5:0.0FA	-0.03%	-0.05%	-0.04%
SCC:6.5:0.0FA	-0.04%	-0.04%	-0.04%
NC:6.5:30FA	-0.03%	-0.04%	-0.05%
SCC6.5:30FA	-0.07%	-0.08%	-0.08%
NC:6.0:30:FA	-0.02%	-0.05%	-0.04%
SCC:6.0:30FA	-0.02%	-0.04%	-0.03%

The SCC:6.5:30FA mix exhibits the largest shrinkage of -0.08% , while its normal concrete shrinkage is -0.05% at 112 days, see Table 23. The amount of shrinkage for other specimens is almost the same (below -0.04%).

The results in Table 23 indicate that the shrinkage of the SCC mixes is almost the same as the NC mixes. These results are expected; since each mix is comprised of the same coarse aggregate, the shrinkage values should not differ by an appreciable amount.

5.5 ASTM C1202-97: Rapid Chlorine Ion Permeability

The rapid chlorine ion permeability test is used to determine the electrical conductance of concrete to indicate its resistance to the penetration of chloride ions. It consists of creating two inch thick slices of concrete, four inches in diameter, and monitoring the amount of electrical current passed through during six hours. These samples have one end placed in a sodium hydroxide solution and one end in sodium chloride. Sixty volts DC is the potential difference maintained across the ends of the specimens, and the total charge passing through relates to the concrete's resistance to chloride ion penetration.

Concrete samples were cut into two inch by four inch diameter pucks here at UND and sent to American Petrographic Services (APS) of Saint Paul, Minnesota. APS did the remaining sample preparation, along with the testing and analysis of eighteen specimens (three per mix design) at the age of twenty-eight days. Table 24 summarizes the results received from APS, and the original reports are presented in Appendix IV.

Table 24: Permeability results.

ASTM C 1202: Rapid Chloride Ion Permeability							
Mix ID	**Coulombs**	**Coulombs**	**Coulombs**	**Avg Total Coulombs**	**Std Dev**	**COV**	**Rating Based On ASTM C 1202**
SCC:6.5:0.0FA	2450	2270	1910	2210	224	10.2%	**Moderate**
SCC:6.5:30FA	1340	2580	1050	1657	813	49.1%	**Low**
SCC:6.0:30FA	1630	1450	1180	1420	185	13.0%	**Low**
NC:6.5:0.0FA	2170	1750	2490	2137	303	14.2%	**Moderate**
NC:6.5:30FA	1120	900	670	897	225	25.1%	**Low**
NC:6.0:30FA	1240	1130	890	1087	146	13.4%	**Low**

Factors known to affect chloride ion penetration include: water-cement ratio, air void system, aggregate type, degrees of consolidation, and type of curing. The permeability results in Table 24 indicate that SCC mixes exhibit comparable permeability to that of the NC mixes. A large deviation between coefficient of variation (COV) for SCC:6.5:30FA (49.1%) and NC:6.5:30FA (25.1%) exists even though the two mixes have similar ingredients, except for HRWRA. This is expected because ASTM allows up to forty-two percent variability for the same mix design tested at the same lab and by the same operator;

in addition, AASHTO allows up to nineteen and half percent variability for the same conditions. This variability allowance explains that the qualitative description of “low,” “moderate,” or “very low” essentially means that concrete mixes falling into the same category are performing the same in the field.

5.6 ASTM C457-98: Linear Traverse

ASMT C457-98 incorporates two methods, linear traverse and modified point count, for estimating the air void parameters of hardened concrete. Due to its well-known accuracy, the linear traverse method was used in this research project.

In a linear traverse, parallel lines are superimposed on a polished plane surface of concrete. Chords are formed by the intersection of these lines with exposed air void sections, and are counted and measured. Air void parameters such as the air content, specific surfaces, and spacing factor are calculated using equations set forth in the test method, and used to gage concrete durability under freezing and thawing (expansion and contraction). The system is automated in the respect that the instrument moves the concrete specimen along a line the exact same distance at each step. The linear traverse method calculates the hardened air content (percent entrained and percent entrapped), air voids per inch, specific surface, spacing factor, paste content, and traverse length. This test, like the chloride ion permeability test was performed by American Petrographic Services, displayed in Figure 38.

Figure 38: American Petrograhpic Services Technician working on a sample of concrete.

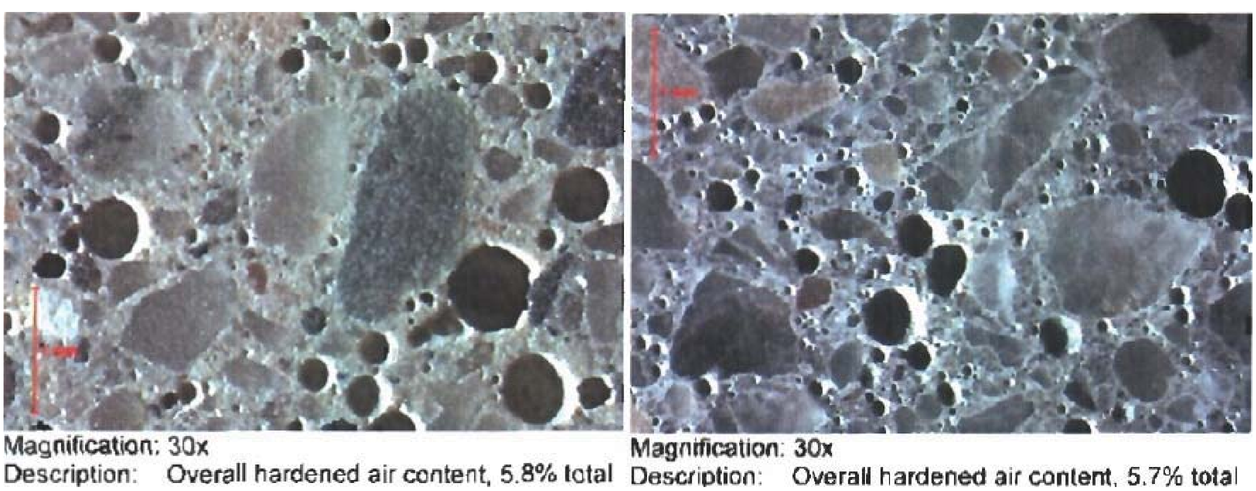
The spacing factor is generally regarded as the most significant indicator of durability of the cement paste matrix to freezing and thawing exposure of concrete. The maximum value of spacing factor for moderate exposure of the concrete is usually taken to be 0.008 inches. Somewhat larger values may be adequate for mild exposure and smaller ones may be required for severe exposure, especially if the concrete is in contact with deicing chemicals. An increase in the water-cement ratio or the paste content must be accompanied by an increase in the air content if the spacing factor is not to increase. The air content can be reduced substantially by extended vibration of the normal concrete without a significant increase of the spacing factor, provided the concrete was adequately air entrained. Extended vibration is not, however, recommended as a field practice because of the dangers of excessive bleeding and segregation.

Table 25 contains the results of linear traverse testing. It is worth noting that ACI 201.2 states that for concrete to have adequate freeze thaw resistance the spacing factor has to be less than 0.008 inches (0.2 mm).

Table 25: Linear traverse test data

Trial #	Mix ID	Air Void Content	% Entrained (≤ 0.04")	% Entrapped (≥ 0.04")	Spacing Factor, (in)	Consistent With Freeze/Thaw Resistance?
5	SCC:6.5:0.0FA	5	3.4	1.6	0.01	no
15	SCC:6.5:30FA	5.4	5.1	0.3	0.006	yes
18	SCC:6.0:30FA	5.8	4.8	1	0.01	no
2	NC:6.5:0.0FA	5.7	4.7	1	0.005	yes
22	NC:6.5:30FA	4.6	4	0.6	0.005	yes
25	NC:6.0:30FA	3.5	3.2	0.3	0.005	yes
Freeze Thaw Limit is set by ACI 201.2						
Max Spacing Factor, to be Freeze/Thaw Resistant					0.008	

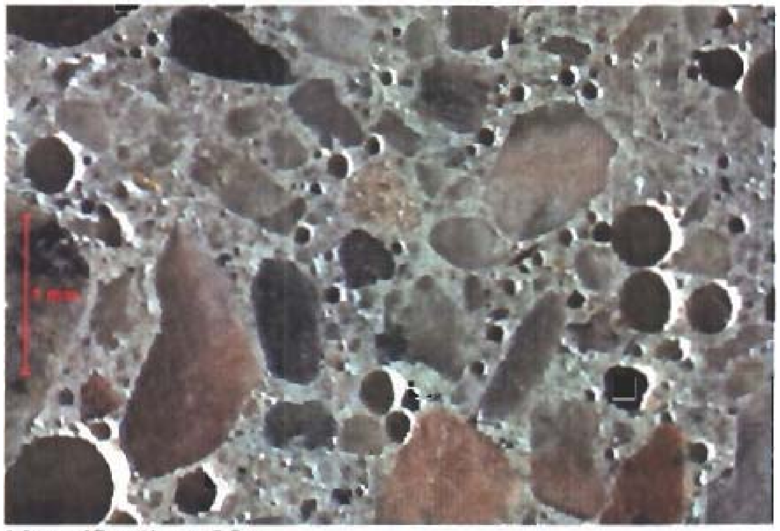
The SCC:6.5:30:FA mix exhibits a spacing factor of 0.006 inches, less than the resistance limit for freeze-thaw of 0.008 inches. The SCC:6.5:0.0FA and SCC:6.0:30FA mixes exhibit a spacing factor of 0.01 inches which are slightly larger than the freeze thaw resistance limit of 0.008 inches. In other words, the air void system was too coarse. Figure 39a shows the image of SCC:6.0:30FA mix with a spacing factor of 0.01 inches, having a larger and less uniform distribution of air-voids as compared to NC:6.5:0.0FA with a spacing factor of 0.005 inches, see Figure 39b and Table 25.



(a) (b)

Figure 39 (a) SCC:6.0:30FA with a spacing factor of 0.01 inches, (b) NC:6.5:0.0FA with a spacing factor of 0.005 inches

The spacing factors for SCC:6.5:0.0FA and SCC 6.0:30FA are 0.01 inches, which are slightly above ACI 201's spacing limit. The SCC:6.5:30FA mix exhibits a spacing factor of 0.006 inches, which is smaller than the spacing limit set by ACI 201. An image of air-void system for SCC:6.5:30FA is illustrated in Figure 40.



Magnification: 30x
Description: Overall hardened air content, 5.4% total

Figure 40: SCC:6.5:30FA, with spacing factor = 0.006"

The results indicate that SCC may be adequate for mild exposure, where as it may not be adequate for severe exposure, especially if the concrete is in contact with deicing chemicals. The SCC mix with 6.5 bag cementitious material containing fly ash exhibits a lower spacing factor and it will be adequate for severe exposure. The details of linear traverse test results are given in Appendix IV.

5.7 ASTM C496-04: Tensile Splitting Test

The tensile splitting test, according to ASTM C496-04, determines the splitting tensile strength (SPTS) of cylindrical concrete specimens. The splitting tensile strength, usually greater than direct tensile strength and lower than flexural strength, is used in design of structural lightweight concrete members. Oftentimes, it is used to evaluate shear resistance for concrete and to determine development length for reinforcement. In this research project, a 6”x12” concrete specimen was laid longitudinally on the testing machine, see Figure 41. A supplementary steel bearing bar twelve inches long with a ½” by 1” cross section was placed in between the ram with a ten inch diameter and the cylinder to cover the length of specimen. Wood shims, three fourths of an inch wide (earring strips), were placed in between the supplementary steel bar and the concrete specimen. Figure 41 shows the test setup.

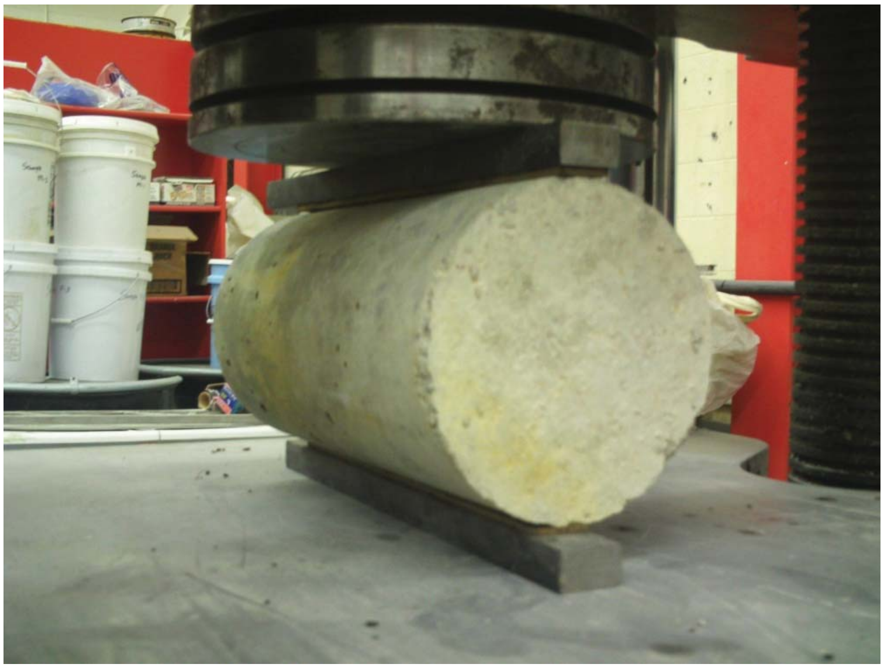


Figure 41: Splitting Tensile Test Setup.

The specimen was loaded uniformly by a hydraulic ram until the member split into two separate pieces along its length. The maximum applied load indicated by the testing machine, along with failure type and concrete appearance, was recorded. Figure 42 shows a typical concrete specimen split after loading.

Figure 42: SCC specimen split after loading.

The splitting tensile strength of the specimen was determined by using the equation:

$$T = \frac{2P}{\pi l d} \tag{11}$$

where:

T = splitting tensile strength, psi

P = maximum applied load indicated by the testing machine, lbf

l = length, in, and

d = diameter, in.

In addition to direct testing, equation 12 can be used to determine SPTS.

$$SPTS = \beta\sqrt{f'_c} \tag{12}$$

where:

β = 6.0 (ACI 318-09, Section R8.6)

β = 7.3 (AASHTO LRFD Bridge Design Manual 2006)

The SPTS obtained from testing are compared to the above equations to evaluate the concrete specimens and to measure accuracy of the testing.

All mixes except for SCC:6.5:30FA had an average splitting tensile strength that was above $6\sqrt{f_c'}$. Table 26 lists the results from the Splitting Tensile strength test.

Table 26: Splitting Tensile test results

Mix ID	fc' (psi)	Measured SPTS	β=6	β
SCC:6.5:0.0FA	7858	587.01	531.88	6.62
NC:6.5:0.0FA	6721	492.19	491.87	6.00
SCC:6.5:30FA	7568	472.65	505.37	5.43
NC:6.5:30FA	5027	472.34	425.41	6.66
SCC:6.0:30FA	6194	574.47	472.21	7.30
NC:6.0:30FA	5228	447.68	433.82	6.19

Observations made from reviewing Table 26 indicate that the tensile strength factor β is 6.60 and 7.30 for SCC:6.5:0.0FA and SCC:6.0:30FA, respectively. The tensile strength for SCC:6.5:0.0FA with β=6.62 is higher than its counterpart NC:6.5:0.0FA with β=6.0. Likewise, SCC:6.0:30FA with β=7.30 has a higher tensile strength than its counterpart NC:6.0:30FA with β=6.19. However, the tensile strength of SCC:6.5:30FA with β=5.43 is less than its counterpart NC:6.5:30FA with β=6.66. This indicates that for concrete with a higher paste ratio, fly ash will increase flowability and may cause lower tensile strength. For concrete with a smaller paste ratio (NC:6.0:30FA), the fly ash has an improving effect on tensile strength. The tensile splitting test results indicate that SCC mixes exhibit comparable tensile strength to their NC counterpart mixes and compare well with the calculated value from the ACI 318 equation.

5.8 ASTM A944-04: Bond Strength

The purpose of the bond strength test, outlined in ASTM A944-04, is to determine the relative bond strength of steel reinforcing bars in concrete and the effect of surface preparation on the bond strength of deformed steel reinforcing bars to concrete.

All pull-out specimens were fabricated and cast in UND’s structural/materials lab.

Actual pull-out testing was performed at Concrete Inc. of Grand Forks, ND by an Enerpac hydraulic jack. The test setup involved laying the pullout specimen on its side and restraining it against movement using steel angles bolted to the floor, as shown in Figure 43.

Figure 43: Pullout Test Setup.

The compression reaction plate was placed with a minimum clear distance of $0.9L_e$, where L_e is embedment length (in), from the center of the test bar to the edge of the plate, as shown in Figure 44. The embedment length L_e is taken as eight inches in this study.

The test specimens contain the test bar cast in a block of reinforced concrete that has the dimensions 24”x15.5”x9.5”, as shown in Figure 44. The specimen was reinforced by four closed stirrups parallel to the sides of the specimen and fabricated from Grade 420 (Grade 60) No.5 bars and test bars of No. 9 (1.128 inch nominal diameter). The two bars provided a total area of more than the test bar. The test bar extended a compatible distance with the test system from the front surface. Two PVC pipes were used as bond breakers to control bonded length and to avoid failure at the loaded end. The concrete block was fabricated to produce strength of 4500 to 5500 psi at the time of testing. The specimens were cured to prevent water evaporation.

Figure 44: Pullout specimen before casting in concrete

The Enerpac hydraulic jack used during testing had a constant load application so the device had to be turned on and off intermittently to reach a predetermined load step where slip of the bar could be recorded, see Figures 45 and 46. Slip measurements were taken on both the front and rear ends of the specimen during loading, see Figure 45 and Figure 46.

Each specimen was loaded to 4,240 pounds of direct tension because it was the smallest load the jack could initiate on startup, and the displacement gages were set to zero. At this point, the specimen was settled in and no shift in position should occur, see Table AV.25.

Measurements at the front of the specimen were calibrated for elastic stretch. Measurements of slip taken at the back side of the specimen, however, were not calibrated for elastic stretch of the bar because direct slip was straight and consistent. A picture of bond slip measurements on the back of the specimen is shown in Figure 46. Results of the slip on the back side of the element are the only slip measurements reported due to their consistency, see Table 27 and Table AV.25 in Appendix V.

Table 27: Slip Data for SCC:6.5:0.0FA

Trial #	6		7	
Psi	Load	Slip "	Load	Slip "
250	4240	0	4240	0
300	5088	0.014	5088	0.00605
600	10176	0.021	10176	0.04375
900	15264	0.0285	15264	0.06435
1000	16960	0.035	16960	0.079095
1100	19147	0.04	19147	0.0822
1200	21333	0.045	21333	0.09
1275	22973	0.051	21880	0.095

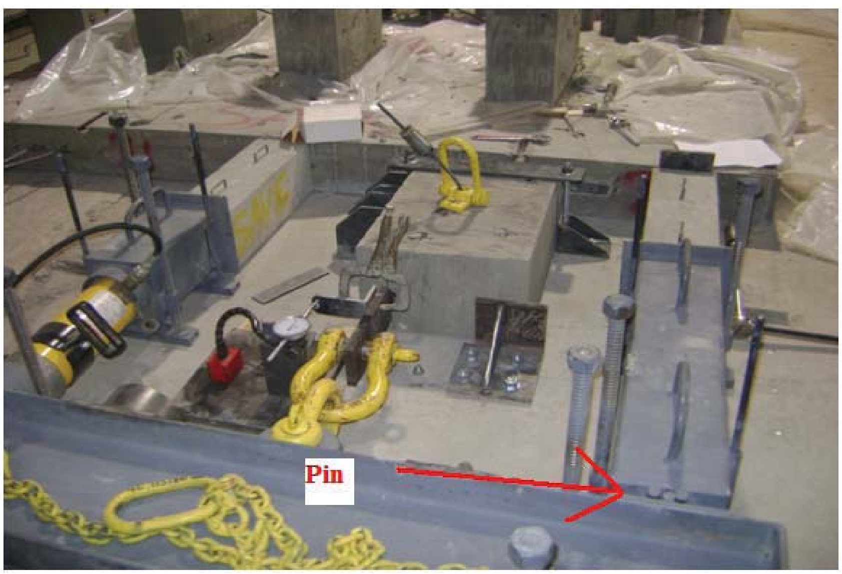


Figure 45: Bond slip measurements on the front of the specimen

Figure 46: Slip measurement taken on the back side of the pull-out specimen

Figure 47 shows that as load is applied to the front end of the specimen, the bar at the rear end of the specimen will move away from the displacement gage.

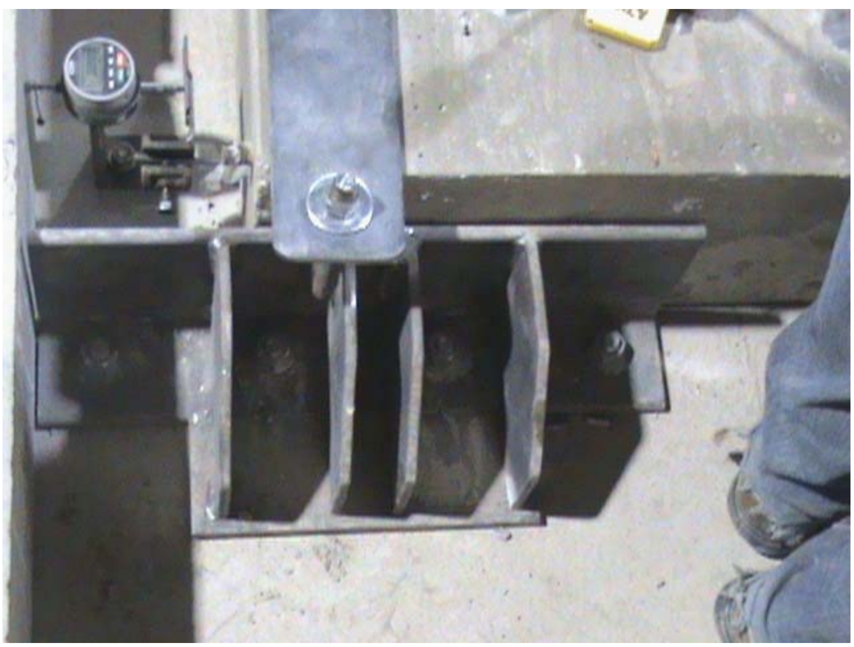


Figure 47: Close-up of displacement gage at the backside of the specimen.

ASTM A944 requires that the relative rib height and center to center spacing of ribs on the rebar be reported. The relative rib used in this research project was 0.1 inches and the center to center spacing was 0.667 inches.

The most important measurement recorded during this test, however, was the tension force that occurs when the bond of the concrete to the rebar can no longer take on load. In most cases, this load point occurred at the first crack, though hairline cracks were observed just prior to the maximum load measurement, see Figure 48. After the specimen was loaded to failure, concrete was knocked away to see if there was adequate consolidation and uniformity.

Figure 48: Typical pullout failure.

Figure 48 shows the clear distance requirement is satisfied because the restraint on the front of the specimen is a clear distance of 7.2 inches away from the test bar ($0.9L_e$, where L_e = 8 inches). All specimens had perfect aggregate distribution with no signs of segregation as seen in Figure 49.

Figure 49: Aggregate distribution uniformity

A total of eighteen pullout specimens were tested (three per mix design), and for each pullout specimen two companion cylinders were tested, according to ASTM C39, to determine their compressive strengths. The pullout specimens were wrapped in plastic to contain all moisture and cured with the companion cylinders at room temperature for twenty-eight days according ASTM A944.

Table 28 lists the average compressive strength and the pullout strength for all pull-out specimens that were tested.

Table 28 Pullout test results

Mix design	Compressive Strength (kips)	Pullout Strength (kips)
SCC:6.5:0.0FA	7323	22427
NC:6.5:0.0FA	6301	17689
SCC:6.5:30FA	5537	16558
NC:6.5:30FA	5207	18399
SCC:6.0:30FA	5863	18094
NC:6.0:30FA	5121	15752

The compressive strength versus the pull-out failure for all mix designs tested are shown in Figure 50.

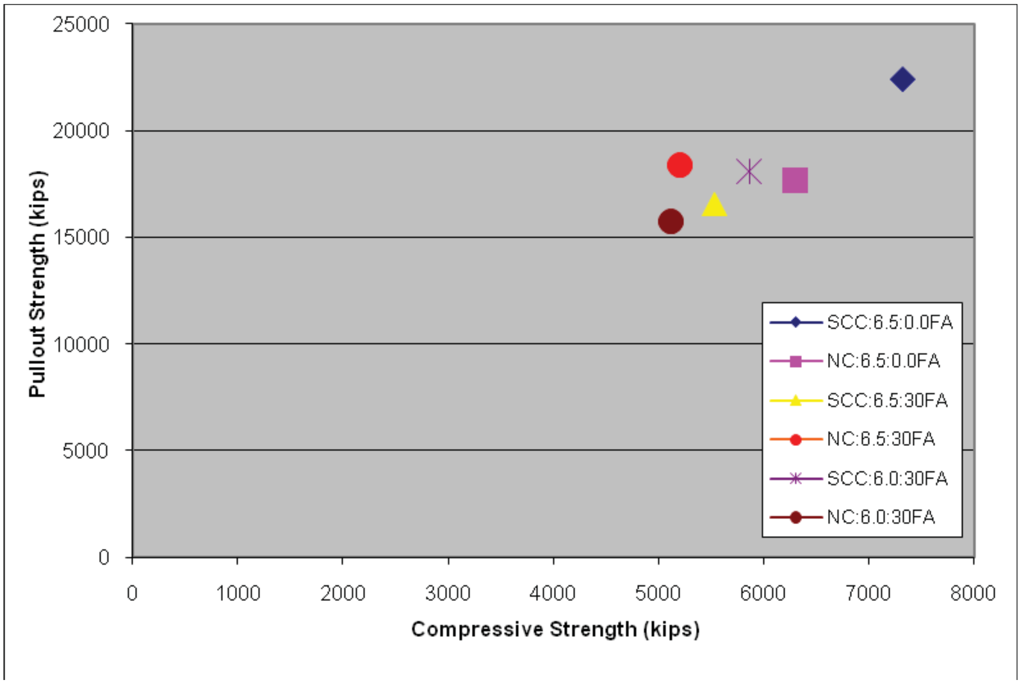


Figure 50: Compressive strength vs. pullout failure

With reference to Table 28 and Figure 50, the following observations and conclusions can be made. The bond strength difference between 6.5 bag mixes and 6.0 bag mixes is very marginal. The SCC:6.5:0.0FA mix exhibits the largest compressive and pullout strengths. The NC:6.0:30FA exhibits the smallest compressive and pullout strength among the tested specimens. In this research project, the bond strength of SCC is being compared to the bond strength of NC. We assume the NC mixes have little or no segregation or bleeding, and that the ASTM A944 test may expose with bleeding problems in SCC mixes. Results of the test explain that due to larger amount of HRWRA present in the SCC mixes, increased compressive strength led to good bond strength. The SCC mixes were simply poured in one continuous lift that provided comparable bond strength as the NC mixes.

It can be concluded that adequate bond strength can be reached using SCC mixes as compared to their corresponding NC mixes.

6. SCC Technology Transfer

The SCC Technology Transfer was intended to distribute the results of the research to the construction community at large. Two field workshops, sponsored by the NDDOT, were held , one in Fargo, ND, on April 20, 2010 and one in Bismarck, ND, on April 27, 2010. The finding of this research was first presented to the attendees of workshops followed by a field demonstration of SCC mix. For each workshop over 40 people attended across the North Dakota including the engineering representatives from NDDOT, suppliers, producers, and contractors. The technology transfer program and feedback from attendees are given in Appendix IV. The finding of this research was also presented at the NDDOT Research Advisory Committee 2010 Annual Meeting in Bismarck.

6.0 CONCLUSIONS

In this project a comprehensive literature review and state department of transportation (DOT) survey was conducted on the present use of SCC in transportation structures. An experimental program was developed to evaluate fresh and hardened properties of self-consolidating concrete (SCC). SCC mixes were compared to conventional concrete (referred to as normal concrete or "NC" from this point forward) mixes that had identical mix proportions with the only difference being admixture levels. High range water reducing admixture (HRWRA) and viscosity modifying admixture (VMA) were used to increase the flow of the experimental mixtures and ASTM testing was used to qualify mixes in the plastic state. Mixes meeting project specifications set by the project technical advisory committee were cast into test specimens.

Hardened property testing was used to evaluate strength, stiffness, permeability, shrinkage, and durability of the concrete mixes. Pullout testing was performed to compare bond strength and linear traverse tests (hardened air void system) were used to investigate freeze thaw durability. Experimental strength and stiffness were evaluated based on ACI 318-08 prediction models for modulus of elasticity and tensile strength.

It was found that the SCC mixes performed as well or better than their conventional mix counterparts in regard to strength and stiffness. However, it was observed that two of the three SCC mixes exhibited slightly higher air void systems as compared to requirements set by ACI 201, ASTM C457 for conventional concrete mixes. It was found that SCC mixes exhibited slightly higher permeability than conventional mixes but are still classified as having "low" permeability according to ASTM C1202. The findings of this research indicate that the bond of SCC to rebar is adequate. The conducted test results in this project prove that SCC can be produced with adequate strength and stiffness in comparison to conventional concrete.

APPENDICES

A.I: Original State Department of Transportation Responses

I.1 Arkansas

- Research Project is ongoing—AHTD project TRC "Investigating the Use of Self Consolidating Concrete in Transportation Structures"

I.2 California

- The California Department of Transportation (Caltrans) has used Self Consolidating Concrete (SCC) on a very notable project, the San Francisco/Oakland Bay Bridge which is currently under construction in a series of contracts. Due to difficult placement conditions the contractor and the state engineers developed SCC for use even though there is not a specification for it. There were many trials and demonstrations to prove to the construction inspectors that the contractor could produce a good SCC consistently. Mock ups were constructed to prove that the concreting would work. There has not been a report written on that work. None the less, modeled on that change order work, a special provision was written on a subsequent project, also on the Bay Bridge.

I.3 Colorado

- Currently used in pre-cast concrete members and as an experimental feature on a project (see report).

I.4 Connecticut

- We accept the use of SCC for precast concrete drainage structures. At this time, this is the only application.
- Research is in-progress regarding a specification for SCC.
- We do have research in progress to conduct a synthesis study to look at what other state agencies are doing, and also to visit precast concrete plants to see to what extent SCC is being used for ConnDOT applications. Currently, some precasters are using SCC exclusively, whereas 6 years ago none of the precasters were using SCC.

I.5 Florida

- We currently allow SCC in prestressed and precast applications. For cast in place applications the mixes are approved on a project by project basis.
- Some general issues that we have noticed about SCC are that contrary to general belief SCC is not just the addition of an admixture to a current mix design. The mix should be designed with the intention of producing SCC properties. SCC requires a change to the coarse to fine aggregate ratio so that additional fines are added to the mix to produce a quality product. In addition there is a real need for close attention to moisture content of aggregates during batching and a need to monitor the moisture content periodically throughout the placement.
- "Mix Design and Testing of SCC using Florida Materials"

Final Report available at:
http://www.dot.state.fl.us/research-
center/Completed_Proj/Summary_SMO/FDOT_BD503_rpt.pdf

I.6 Georgia

- We do allow SCC for prestressed concrete girders, however, at this time the precast producers have not cast any beams utilizing SCC.

I.7 Idaho

- SCC currently used for voided box girders, MSE and sound wall panels

I.8 Illinois

- SCC is allowed for cast-in-place and precast. SCC is still being evaluated for precast prestressed.
- IDOT's Final Report on Self-Consolidating Concrete available at:

http://www.ict.uiuc.edu/Publications/report%20files/FHWA-ICT-08-020.pdf

I.9 Iowa

- We use SCC mostly in Precast. One prestressed fabricator is using SCC to fabricate beams. There are few instances where we used SCC for cast-in-place construction.

- We are currently working on the specification on SCC.

I.10 Kentucky

- Kentucky currently only allows SCC in precast plant facilities.
- KYTC's Specification taken from
  http://transportation.ky.gov/materials/download/kymethods/km32008.pdf
  Kentucky Method 64-320-08
  Revised 03/21/08
  Supersedes 64-320-06
  Dated 03/03/06

I.11 Maryland

- Currently we are using SCC in limited applications for precast drainage structures. At the present time we do not allow the use of SCC for structural prestressed concrete.
- We are working on a draft spec at the present time and intend to have final version by year's end.

I.12 Massachusetts

- SCC used in Precast/Prestressed concrete products.
- We require 25 in. flow and 3 1/2% air.

I.13 Michigan

No Response, just contact information. Contact Information is listed in Appendix I.

I.14 Minnesota

- We have used SCC in a couple of limited cases.

a) Retrofit repairs on the Wakota Bridge where consolidation by conventional means was impossible

b) Drilled shafts on I-35W

c) Limited use in the precast area

- The U of M is in the final revisions of a report they are working on, looking at SCC in precast beams.

Robert G. Moore of SRF Consulting Group is very knowledgeable about SCC, he performed all construction inspection for MNDOT on the I-35W drilled shafts that supported the bridge abutments. Robert Moore can be reached at:

One Carlson Parkway North, Suite 150
Minneapolis, MN 55447-4443
bmoore@srfconsulting.com
612-210-9563 cell
763-475-0010 main

I.15 Nebraska

- Applications using SCC: PreCast/Prestressed Girders, Piles, Special Cast-In-Place Applications (such as congested diaphragms)
- Attached are special provisions that were developed for specific Cast in Place SCC applications. Also attached is the corresponding file used by NDOR to document that the mix design developed by the supplier has successfully achieved NDOR's predefined requirements for each application. NDOR uses this process to designate the supplier as a certified entity to supply the material.
- An additional policy is currently under development between NDOR and precast/prestressed suppliers, in order to establish a new process of SCC mix design acceptance and inspection procedures for prestressed/precast applications ….this policy may be available within the next month or two.
- The purpose of this research project was to verify that we could produce a SCC mix that could be used in the field, using local materials available in Nebraska. The PI was able to produce a mix that met our physical and mechanical requirements, using local material and was pump-able without causing segregation. NDOR developed a specification for SCC CIP after this project was completed.
- The researchers also developed an extremely general guide to using SCC in the field; it is attached for your reference…however NDOR does not refer to this document in any of our acceptance policies or specifications. The special provisions are what we use in practice.

I.16 New Jersey

- Research Final report is to be published in the next few months.

I.17 New Mexico

- No SCC use, however, we have opened the opportunity, if driven by the contractor.
- Have conducted research, although the report is not available.

I.18 New York

- SCC is used for precast concrete operations routinely where the precaster designs the mixture and acceptance is based on performance criteria of air content and compressive strength. Precast requirements for Materials elements (everything but bridge beams and 3-sided structures is covered in out standard specifications Section 704-03 but no specific reference / requirements to SCC exist, strictly performance.
- Structural items are handled by the Department's Structures group and each precast develops and pre-qualifies and HPC mixture that may or may not use SCC - there is no requirement to use SCC, just the allowance to do so.
- Cast-In-Place construction using SCC is increasing and we're finding for some it is the concrete of choice. Use of SCC for CIP applications is handled by a special note included in proposals. Once enough contractors and producers have acceptable experience with SCC we intend to incorporate the SCC requirements into our standard specifications.
- The only specifications making specific reference to SCC are the special notes referenced above for CIP construction. The special notes are attached for your use.
- No "formal" research has progressed. Investigation into the use in Materials precast items determined the plastic and hardened air contents to be identical, no freeze-thaw concerns, and no strength development concerns. The CIP use has been trial and error (fortunately with little error!)

I.19 Ohio

- Ohio has used the materials. We see a fair amount of use in precast. Some in railing for cast in place concrete. Have had a single use of SCC in large column pours where possible rebar congestion issues are.

I.20 Oregon

- Currently the largest use is for precast prestressed concrete bridge members. We have also used for precast concrete manhole sections. We don't have a specification, but typically our Structure Services Engineer will review the manufacturer's proposed specification and approve as appropriate. We do, however, have plans to develop a specification.

I.21 Rhode Island

No Response, just contact information which is listed in Appendix I.

I.22 South Carolina

- SCDOT currently has research underway with the University of South Carolina to study the use of SCC using lightweight aggregate in prestressed beams, however no report has been prepared at this time. Additionally, our Bridge Design section has completed research on one project in conjunction with Auburn University using SCC in a drilled shaft and has another project underway with the University of South Carolina looking at SCC in prestressed bridge beams. You may wish to contact Mr. Bener Amado for information about those particular projects.

I.23 South Dakota

- Currently we are doing some Box Culverts, this is part of the implementation of a research project being done for SDDOT by SDSU. We also have a research project ongoing evaluating the use of SCC in Bridge Girders.

I.24 Texas

- Currently used in traffic barriers, manholes, and inlets.
- Currently using PCI's - "Interim Guidelines for the use of Self Consolidating Concrete" at http://www.pci.org/view_file.cfm?file=TR-6-03_PCI_SCC_GUIDELINES.PDF
- Currently TxDOT has funded a research project, Self-Consolidating Concrete for Precast Structural Applications, to confirm the design parameters of the fresh

concrete properties, early age hardened properties, and later age hardened properties in prestressed girders.

- The first half is available at: www.utexas.edu/research/ctr/pdf_reports/0_5134_1.pdf.
- The second half of the research report is to be available soon at http://tti.tamu.edu/.

I.25 Virginia

- Other VTRC reports titles are:

  Investigation of Fiber Reinforced Self-Consolidating Concrete
  Shear Strength of PCBT-53 Girders Fabricated with Light-Weight, Self-Consolidating Concrete
  At http://vtrc.virginiadot.org/PUBS.aspx

I.26 Washington

- Currently the Self Compacting Concrete Specifications are located in the 2008 Washington DOT Standard Specifications in Sections 6-02.3(27) Concrete for Precast Units, and 6-10.3(1) Precast Concrete Barrier.

The 2008 Washington DOT Standard Specifications (M 41-10) is available on line at: http://www.wsdot.wa.gov/Publications/Manuals/index.htm

- WSDOT also uses the attached BSP for the Tacoma Narrows noise walls as well as the Fredonia test shafts.
- WSDOT conducted an experiment on the construction of two 6' diameter 50' deep wet drilled shafts for the Fredonia test shafts with SCC and the results of the experiment were excellent. The research is a combined report with WSDOT and Caltrans participating along with the University of Reno. The WSDOT portion of the report is expected to be available within the next year. Mo Sheikhizadeh has the raw information and is willing to discuss if you give him a call.

I.27 West Virginia

- We allow it to be used in precast concrete but we don't require it. However, we don't allow it to be used in prestressed concrete applications.

- We are in the process of putting together a special provision for SCC that will be used on an upcoming project as a trial. Some of the elements on that project (a couple of prestressed concrete box beams and a few drilled shafts) will be constructed using SCC.
- We have a current research project on SCC. The research hasn't been completed yet, so the final report isn't available.

I.28 Wisconsin

- WisDOT does not use SCC on a regular basis. We had one large project, Marquette Interchange in Milwaukee where we did use SCC for precast prestressed architectural wall panels that were used as facing on large secant pile retaining wall structures. Those were cast laying flat in the beds, and turned out with very excellent appearance.

I.29 Wyoming

No response, just contact information which is listed in Appendix II.

Table AI.1: SCC contact list A-M.

State	Contact	Title	Phone	Cell	Fax	Address	E-mail
Arkansas	Wayne Casteel	Concrete and Steel Fabrication Engineer	501-569-2390	NA	NA	NA	NA
California	Doran Glauz	NA	NA	NA	NA	NA	doran_glauz@dot.ca.gov
Colorado	Eric Prieve	PE, I	303-398-6542	303-204-8926	303-398-6540	Concrete and Physical Properties 4670 North Holly St; Unit A Denver, CO 80216-6408	NA
Connecticut	John Henault	Transportation/ Principal Investigator for ConnDOT's research with SCC	860-258-0352	NA	860-258-0399	Division of Research 280 West St Rocky Hill, CT 06067	john.henault@po.state.ct.us
Florida	Michael Bergin	PE, State Structural Materials Engineer	352-955-6666	352-260-7090	NA	State Materials Office Gainesville, FL 32609	michael.bergin@dot.state.fl.us
Georgia	Myron K. Banks	Materials & Research Branch Chief - Concrete	404-363-7561	NA	404-363-7669	NA	NA
Idaho	Clint Hoops	PE	208-334-4415	NA	NA	NA	clint.hoops@itd.idaho.gov
Illinois	Doug Dirks	Engineer of Concrete and Soils	212-782-7208	NA	NA	NA	NA
Iowa	NA	NA	NA	NA	NA	NA	NA
Kentucky	Ross Mills	NA	NA	NA	NA	NA	ross.mills@ky.gov
Maryland	Paul Finnerty	Chief, Concrete Technology Division	443-572-5133	NA	NA	NA	pfinnerty@sha.state.md.us
Massachusetts	Ruce Noyes	NA	617-951-1367	NA	NA	NA	NA
Michigan	John F. Staton	PE, Engineer of Materials	517-322-5701	NA	517-322-5664	Construction and Technology Division P.O. Box 30049 8885 Ricks Road Lansing, MI 48090	NA
Minnesota	Ronald Mulvaney	PE, Assistant Concrete Engineer	651-366-5575	651-334-8144	651-366-5530	Office of Materials - Mail Stop 645 1400 Gervais Avenue Maplewood, MN 55109-2044	ronald.mulvaney@dot.state.mn.us

Table AI.2: SCC contact list N-Z.

State	Contact	Title	Phone	Cell	Fax	Address	E-mail
Nebraska	Lieska Halsey	NA	402-479-3861	NA	NA	NA	lieska.halsey@nebraska.gov
Nebraska	Amy Starr	NA	402-479-3687	NA	NA	NA	amy.starr@nebraska.gov
New Jersey	Eileen Sheehy	NA	609-530-2307	NA	NA	NA	eileen.sheehy@dot.state.nj.us
New Mexico	Bryce Simons	Materials Testing Engineer	505-827-5191	505-470-7902	NA	NA	NA
New York	Donald A. Streeter	PE	518-457-4593	NA	518-457-8171	NA	NA
Ohio	Lloyd Welker	NA	614-275-1351	NA	NA	NA	NA
Ohio	Byan Struble	NA	614-275-1325	NA	NA	NA	NA
Oregon	Keith Johnson	Structural Services Engineer	503-986-3053	NA	NA	NA	NA
Rhode Island	Mark E. Felag	PE, Managing Engineer Materials	401-222-2524 x-4130	401-641-8279	401-222-2524	NA	NA
South Carolina	Bener Amado	NA	803-737-0181	NA	NA	NA	amadob@scdot.org
South Carolina	Aly Hussein	Structural Materials Engineer	803-737-6687	NA	NA	NA	husseinAA@scdot.org
South Dakota	Darin Hodges	Concrete Engineer	605-773-7193	NA	NA	NA	darin.hodges@state.sd.us
Texas	Jason Tucker	PE, Construction Division	512-506-5935	NA	NA	NA	JTUCKE1@dot.state.tx.us
Virginia	Larry Lundy	NA	804-328-3130	NA	NA	NA	larry.lundy@vdot.virginia.gov
Virginia	Celik Ozyildirim	Member of Virginia Transportation Research Council	434-293-1977	NA	NA	NA	celik@vdot.virginia.gov
Washington	Mo Sheikhizadeh	Bridge Construction Manager	360-705-7828	NA	NA	NA	SHEIKHM@wsdot.wa.gov
Washington	Kurt Williams	Construction Materials Engineer	360-705-7828	NA	NA	NA	WILLIKR@wsdot.wa.gov
Wisconsin	James M. Parry	Quality Assurance Supervisor	608-246-7939	NA	NA	NA	james.parry@dot.state.wi.us
Wyoming	Bob Rothwell	Assistant State Materials Engineer	307-777-4476	NA	NA	NA	bob.rothwell@dot.state.wy.us

Table AI.3: Summary of SCC applications in each state. CIP stands for cast in place.

		Applications						
State	**SCC Use**	**Prestressed**	**CIP**	**Non-structural Precast**	**Special App**	**Specification**	**Research Report**	**Comments**
Arkansas	No	No	No	No	No	No	On going	NA
California	Yes	NA	NA	NA	No	No	None at this time	Use has been on Oakland/SF Bay Bridge
Colorado	Yes	No	No	No	Yes	No	Yes	See Report
Connecticut	Yes	Yes	No	No	No	No	In progress	Visiting precast plants to see what extend SCC is being used on ConnDOT app. Some
Florida	Yes	Yes	No	No	No	No	http://www.dot.state.fl.us/research-center/completed_Proj/Summary_SMO/FDOT_BD503_rpt.pdf	Adjust CA/FA ratio and pay close attention to free moisture
Georgia	Yes	yes	No	No	No	No	NA	NA
Idaho	Yes	Yes	No	Yes	Sound walls	Yes	NA	NA
Illinois	Yes	No, evaluation underway	Yes	Yes	NA	NA	http://www.ict.uiuc.edu/Publications/report%20files/FHWA-ICT-08-020.pdf	No
Iowa	Yes	Yes	Yes	Yes	NA	In progress	NA	NA
Kentucky	Yes	Yes	No	Yes	NA	Yes	NA	NA
Maryland	Yes	No	No	Yes	Drainage strucutures	NA	NA	NA
Massachusetts	Yes	Yes	No	Yes	No	25" min spread and 3.5 +,- 1% Air	NA	NA
Minnesota	Yes	No, evaluating	Yes	Yes	Retrofit	NA	U of M is in final revisions	Limited use, case by case basis
Nebraska	Yes	Yes	Yes	Yes	Piles	Yes	SPR-1(07) 594	Use special provisions
New Jersey	Yes	Yes	Yes	Yes	Drilled Shafts	Yes	NA	NA
New Mexico	No	-	-	-	-	-	-	use can be used if contractor proposed
New York	Yes	yes	yes	Yes	NA	Optional Note	None at this time	Spec for structural apps is strictly performance, SCC is merely an option, all mixes have to be prequalified. Once contractors have more
Ohio	yes	yes	Yes	Yes	NA	NA	None at this time	Limited use, case by case basis
Oregon	Yes	Yes	No	Yes	precast manholes	None at this time	None at this time	Spec in development
Rhode Island	NA							
South Carolina	No	No	No	No	No	Under development	Research is on going	Two research projects are ongoing one dealing with SCC in drilled shaft construction and another with lightweight agg/SCC mix in prestress app
South Dakota	yes	No	No	yes	box Culverts	Special Provision	Research is on going with SDSU	NA
Texas	Yes	No	yes	Yes	barriers, manholes, inlets	use PCI's interim Guidelines	Interim report available from UT Austin, www.utexas.edu/research/ctr/pdf_reports/0_5134_1.pdf	2nd report will come out of Texas A&M in 2009
Virginia	yes	yes	yes	yes	NA	yes, rough draft	http://vtrc.virginia.org/PUBS.aspx	Virginia a leader in SCC research
Washington	yes	Yes	yes	yes	Sound walls, test shafts	yes	None at this time	NA
West Virginia	yes	No	No	Yes	No	No	On going	In process of evaluating SCC for structural and stressed applications
Wisconsin	yes	In-process of approving	No	Yes	sound walls	no	Yes, see Appendix III	Used SCC on the Marquette Interchange in Milwaukee on non-structural items.

AII: Existing State Specifications

II.1 Georgia

Georgia Department of Transportation
State of Georgia
Special Provision
PROJECT NO.:
P.I. NO.:

Section 500—Concrete Structures

Delete Subsection 500.1 and substitute the following:

This work consists of manufacturing and using High Performance Self-Consolidating Concrete to construct precast-prestressed concrete bridge members as shown in the Plans.

Add the following to Subsection 500.1.01:

High Performance Self-Consolidating Concrete (SCC): a highly workable concrete that can flow through dense reinforcement under its own weight and adequately fill voids without segregation or excessive bleeding without the need for vibration.

Add the following to Subsection 500.1.02.A:

Section 831—Admixtures

Add the following to Subsection 500.1.02.B:

AASHTO T 277

PCI Guideline TR-6-03

GDT 26

GDT 32

GDT 122

Delete Subsection 500.1.03.A and substitute the following:

II.1.1. Concrete Mix Designs

The Contractor is responsible for all concrete mix designs. Ensure that concrete mixes contain enough cement to produce performance requirements within the water-cement ratio specified in Table II.1—High Performance Self-Consolidating Concrete Mix Design Table, below.

Submit a mix design for approval to the Office of Materials and Research. Include the sources, actual quantity of each ingredient, fine and coarse aggregate gradations, including gradation curves, design slump flow, design air and laboratory results that demonstrate the ability of the design to attain both the required compressive strength and chloride permeability.

Include laboratory results of the slump flow (spread) test, T-20 inch (T-500 mm) test, Visual Stability Index (VSI) Rating test, and either the L-Box test or U-Box test (all sampled and tested according to PCI Guideline TR-6-03), air content (according to GDT 26 or GDT 32), fresh concrete temperature (according to GDT 122) of at least two or more separate batches.

Include laboratory compressive strength test results tested according to AASHTO T 22 of at least two 1 day, two 3 day, two 7 day, eight 28 day and six 56 day test cylinders prepared according to PCI Guideline TR-6-03. Ensure these test cylinders are made from two or more separate batches with an equal number of cylinders made from each batch. Include laboratory chloride permeability test results, at 56 days, of at least two test specimens prepared and tested according to AASHTO T 277. Ensure these test specimens are made from two or more separate batches with an equal number of specimens made from each batch.

Table AII.1—High performance Self-Consolidating Concrete mix design

English										
Class of Concrete	Maximum Water/ Cement Ratio (lbs/lbs)	L-Box Test Blocking Ratio H1/H2 Min	Max	H-Box Test Blocking Ratio H1/H2 Min	Max	Slump Flow (in) Minimum	Entrained Air (%) Min	Max	Minimum Compressive Strength at 28 days (psi)	Maximum Chloride Permeability at 56 days (Coulombs)
"AAA SCC"	0.350	0.8	1.0	0.75	1.0	20 (Time 20 in = 3 to 8 seconds)	3.5	6.5	5000 psi or as shown on the Plans	Beams – 4000 Piling – 2000 or as shown on the plans

Metric										
Class of Concrete	Maximum Water/ Cement Ratio (lbs/lbs)	L-Box Test Blocking Ratio H1/H2 Min	Max	U-Box Test Blocking Ratio H1/H2 Min	Max	Slump Flow (mm) Minimum	Entrained Air (%) Min	Max	Minimum Compressive Strength at 28 days (MPa)	Maximum Chloride Permeability at 56 days (Coulombs)
"AAA SCC"	0.350	0.8	1.0	0.75	1.0	500 (Time 500 mm = 3 to 8 seconds)	3.5	6.5	35 MPa or as shown on the Plans	Beams – 4000 Piling – 2000 or as shown on the plans

As part of the mix design approval, the Contractor shall construct a test piece using the proposed SCC mix. This test piece shall be a mock-up of the precast element (i.e., beam, pile, etc). The test piece shall have the same dimensions of the precast element, except the minimum length shall be 10 feet (3 m). The test piece shall have the same bar reinforcement, pretensioning strand geometries, block outs and any other items required that will replicate a test pour of the complex portions of the precast element.

The Contractor shall use production equipment and operations to demonstrate concrete production, delivery, placement, finishing and curing. During concrete placement, the proposed mix will be evaluated for workability, flow and bleeding. After the concrete has cured, the forms will be removed and the concrete will be evaluated for surface finish and voids. The mock-up shall not be vibrated.

Add the following to Subsection 500.2

Use aggregates manufactured to meet the gradation at the quarry or blended at the plant site to produce the desired results. Use aggregates that are well graded without gradation gaps.

Add the following to Subsection 500.2 Table II.2:

Table AII.2: Materials

Material	Section
Raw or Calcined Natural Pozzolan (4)	831.2.03.A.2
Microsilica (Silica Fume)	831.2.03.A.4

Delete Note 2 of Subsection 500.2 Table II.2 and substitute the following:

2. Use Type I or III Portland cement in High Performance Self Consolidating concrete. Do not use air-entraining cement.
4. Use Metakaolin as the raw or calcined natural Pozzolan unless otherwise specified.

Delete Note 2 of Subsection 500.2 Table II.2 and substitute the following:

2. Use Type I or III Portland cement in High Performance Self Consolidating concrete. Do not use air-entraining cement.
4. Use Metakaolin as the raw or calcined natural Pozzolan unless otherwise specified.

Delete Subsections 500.3.04.D.3, 4 and 5 and add the following:

3. Water-Reducing Admixtures

The Contractor may use Type F or G high range water-reducing admixtures in combination with water-reducing admixtures or mid range water-reducing admixtures. Ensure that the SCC mix meets the requirements of Subsection 500.1.03.A.3 and that water-reducing admixtures meet the requirements of Subsection 831.2.02, “Chemical Admixtures for Concrete”.

4. Viscosity Modifying Admixtures

The Contractor may use viscosity modifying admixtures (VMA) to attain the desired SCC performance. When using a VMA, ensure that the SCC mix meets the requirements of Subsection 500.1.03.A.3 and that the VMA causes no harmful effects in the hardened concrete.

5. Supplementary Cementitious Materials

The Contractor may use supplementary cementitious materials (SCMs) as additives in SCC to promote workability, plasticity and high-early strengths. The Contractor may use SCMs as a partial replacement for Portland cement in SCC if the following limits are met:

a. No more than three SCMs can be used in a SCC mixture.

b. When one SCM is used, replace no more than 20 percent of the cement by weight.

c. When two or three SCMs are used, replace no more than 40 percent of the cement by weight.

d. The SCMs can be fly ash, ground iron blast furnace slag, microsilica or metakaolin used singly or in combination.

e. Calculate the water-cement ratio based on the total cementitious material in the mix including all SCMs.

f. Fly Ash

- If Class F or Class C fly ash is used, the loss of ignition of the fly ash shall not exceed 3 percent.
- Ensure that the fly ash mix meets the requirements of Subsection 500.1.03.A.3 and Subsection 831.2.03.A.1, “Fly Ash”.

c. Granulated Iron Blast-Furnace Slag

- Ensure that the slag mix meets the requirements of Subsection 500.1.03.A.3 and Subsection 831.2.03.A.3, “Granulated Iron Blast-Furnace Slag”.

d. Microsilica

- Ensure that the microsilica mix meets the requirements of Subsection 500.1.03.A.3 and Subsection 831.2.03.A.4, “Microsilica”.

e. Metakaolin

- Ensure that the metakaolin mix meets the requirements of Subsection 500.1.03.A.3 and Subsection 831.2.03.A.2, “Raw or Calcined Natural Pozzolan”.

Add the following to Subsection 500.3.06:

IV.1.2. Concrete Mix Acceptance Tolerances of Fresh Concrete

Immediately before placement, perform and record the results of the following tests:

1. Concrete temperature tested according to GDT 122 will be 50°F (10°C) to 95°F (35 °C).
2. Slump flow (spread) tested according to PCI Guideline TR-6-03 will be +/- 2 in (50 mm) from design slump flow.
3. Air content tested according to GDT 26 or GDT 32 will be 3.5% to 6.5%.

IV.1.3 Concrete Acceptance of Hardened Concrete

1. Minimum compressive strength at 28 days tested according to AASHTO T 22 will be 5000 psi (35 MPa) or as shown on the plans.
2. Maximum chloride permeability at 56 days tested according to AASHTO T-277 will be the following:

    Beams – 4000 Coulombs or as shown on the plans

    Piling - 2000 Coulombs or as shown on the plans

II.2 Idaho

II.2.1 ITD's SCC Specification

Self Consolidating Concrete (SCC)

Description. Self Consolidating Portland cement concrete shall be proportioned and mixed in accordance with these specifications and placed in reasonably close conformity with the lines and grades shown on the plans or established.

The Contractor shall submit a proposed mix design to the Engineer for review. The Engineer will review the mix design for compliance with specifications prior to approving use of the proposed mix design.

The class concrete shall be as shown on the drawings or as specified in the corresponding items on the bid schedule.

A. *Classification.* The following classes of concrete shall be used where required in the plans:

Table AII.3: Basic mix design parameters (English units)

Concrete Class in 100 psi (28 Day)[a][f]	Max. Water To Cement Ratio [b]	Flow in	Visual Stability Index	Air Content Percent
35 and greater **(c)(d)(e)**	.40	20 - 30	1.5 max	0-6
30	.45	18 - 32	1.5 max	6.5±1.5

(a) Numerical part of class designation is the specified compressive strength when tested in accordance with applicable test listed in Materials.

(b) Cement + Secondary Cementious Materials, if used.

(c) Concrete classes designated as "A" shall have an air content of 6.5±1.5 percent.

(d) Concrete classes designated as "B" shall have 6.5±1.5 percent.

(e) Concrete classes designated as "C" shall have a maximum water cement ratio of 0.38, (water reducer required), and air content of 6.5±1.5 percent.

(f) Concrete shall utilize fly ash when designated with an "F". This designation when used with the above designations will indicate a mix containing fly ash and meeting the requirements for an "A", "B" or "C" mix as specified.

Secondary Cementious Materials. Fly ash, if used, shall be Class F. Ground Granulated Blast Furnace Slag (GGBFS) shall meet ASTM C989, Grade 100. Fly ash shall not exceed 30 percent of the total cementious material (fly ash + cement). GGBFS, if used, shall not be more than 35 percent of the total cementious materials.

Unless otherwise provided, concrete shall be Class 30 (Class 20.5) and the coarse aggregate used in any class of concrete shall be size No. 2. Should an increase or decrease in flow be desirable for the concrete as batched, the aggregate blend or the additive dosages may be adjusted. In no case, may the adjustment to either the coarse or fine aggregate exceed 100 lbs (60 kg). The ratio of the weight of water to cement shall be maintained.

Acceptance. Acceptance of self consolidating concrete shall be in accordance with Subsection 502.01.

Materials. Materials requirements shall correspond with those set forth in Subsection 502.02.

Testing shall be in accordance with the applicable test methods listed under Subsection 502.02 as modified by PCI TR-6-03, "**Interim Guidelines for the Use of Self-Consolidating Concrete"** and the following test methods:

Standard Test Method for Slump Flow of Self-Consolidating Concrete …. ASTM C 1611
Passing Ability of Self-Consolidating Concrete by J-Ring ………………… ASTM C 1621
Visual Stability Index ………………………………………………………PCI TR-6-03

Construction Requirements. Proportioning, equipment, handling, measuring, batching, mixing, delivery, forming, placing, finishing and curing of concrete *s*hall be in accordance with applicable portions of Subsection 502.03.

Method of Measurement. Self Consolidating Concrete will be measured as specified under the respective item in the bid schedule.

Basis of Payment. Payment for accepted quantities of this item will be paid for as specified under the respective item in the bid schedule.

II.3 Illinois

II.3.1 SCC for Precast Products

Effective: July 1, 2004,

Revised: January 1, 2007

Definition. Self-consolidating concrete is a flowable mixture that does not require mechanical vibration for consolidation. Usage. Self-consolidating concrete may be used for precast concrete products. Materials..Materials shall be according to Section 1021 of the Standard Specifications. Mix Design Criteria. The mix design criteria shall be as follows:

(a) The minimum cement factor shall be according to Article 1020.04 of the Standard Specifications. If the maximum cement factor is not specified, it shall not exceed 7.05 cwtlcu yd (418 kg/cu m).

(b) The maximum allowable water/cement ratio shall be according to Article 1020.04 of the Standard Specifications or 0.44, whichever is lower.
(c) The slump requirements of Article 1020.04 of the Standard Specifications shall not apply.
(d) The coarse aggregate gradations shall be CA 13, CA 14, CA 16, or a blend of these gradations. CA 11 may be used when the Contractor provides satisfactory evidence to the Engineer that the mix will not segregate. The fine aggregate proportion shall be a maximum 50 percent by weight (mass) of the total aggregate used.
(e) The slump flow range shall be ± 2 in. (± 50 mm) of the Contractor target value, and within the overall Department range of 20 in. (510 mm) minimum to 28 in. (710 mm) maximum.
(f) The visual stability index shall be a maximum of 1.
(g) The J-ring value shall be a maximum of 4 hi. (100 mm). The Contractor may specify a lower maximum in the mix design.
(h) The L-box blocking ratio shall be a minimum of 60 percent. The Contractor may.specify a higher minimum in the m'ix design.
(i) The column segregation index shall be a maximum 15 percent. 0) The hardened visual stability index shall be a maximum of 1.

Placing and Consolidating. The maximum distance of horizontal flow from the point of deposit shall be 25 ft (7.6 rn), unless approved otherwise by the Engineer.
Concrete shall be rodded with a piece of lumber, conduit, or vibrator if the material has lost its fluidity prior to placement of additional concrete. The vibrator shall be the pencil head type with a maximum diameter or width of 1 in. (25 mm). Any other method for restoring the fluidity of the concrete shall be approved by the Engineer.
Mix Design Approval. The Contractor shall obtain mix design approval according to the Department's Policy Memorandum "Quality Control/Quality Assurance Program for Precast Concrete Products".

II.3.2 SCC for Cast-In-Place Construction
Effective: November 1 , 2005
Revised: January 1, 2007

Definition. Self-consolidating concrete is a flowable mixture that does not require mechanical vibration *for* consolidation .

Usage. Self-consolidating concrete may be used for cast-in-place concrete construction items involving Class MS, DS, and SI concrete.

Materials. Materials shall be according to Section 1021 of the Standard Specifications.

Mix Design Criteria. Article 1 020.04 of the Standard Specifications shall apply, except as follows:

(a) The cement factor shall be according to Article 1020.04 of the Standard Specifications. If the maximum cement factor is not specified, it shall not exceed 7.05 cw/cu yd (418 kg/cu m). The cement factor shall not be reduced if a water-reducing, retarding, or high range water-reducing admixture is used.

(b) The maximum allowable water/cement ratio shall be according to Article 1020.04 of the Standard Specifications or 0.44, whichever is lower.

(c) The slump requirements shall not apply.

(d) The coarse aggregate gradations shall be CA 13, CA 14, CA 16, or a blend of these gradations. CA 11 may be used when the Contractor provides satisfactory evidence to the Engineer that the mix will not segregate. The fine aggregate proportion shall be a maximum 50 percent by weight (mass) of the total aggregate used.

(e) The slump flow range shall be ± 2 in. (± 50 mm) of the Contractor target value, and within the overall Department range of 20 in. (510 mm) minimum to 28 in. (710 mm) maximum.

(f) The visual stability index shall be a maximum of 1.

(g) The J-ring value shall be a maximum of 4 in. (100 mm). The Contractor may specify a lower maximum in the mix design.

(h) The L-box blocking ratio shall be a minimum of 60 percent. The Contractor may specify a higher minimum in the mix design.

(i) The column segregation index shall be a maximum 15 percent.

(j) The hardened visual stability index shall be a maximum of 1.

Test-Methods Illinois Test Procedures- SCC-1,-SCC-2;-SCC-3; SCC-4,SCC-5, SCC-6,and Illinois Modified AASHTO T 22, 23, 121, 126, 141, 152, 177, 196, and 309 shall be used for testing of self-consolidating concrete mixtures.

Mix Design Submittal. The Contractor's Level III PCC Technician shall submit a mix design according to the "Portland Cement Concrete Level III Technician" course manual, except target slump information is not applicable and will not be required. However, a slump flow target range shall be submitted. In addition, the design mortar factor may exceed 1.10 and durability test data will be waived. ~

A J-ring value shall be submitted if a lower mix design maximum will apply. An L-box blocking ratio shall be submitted if a higher mix design minimum will apply. The Contractor shall also indicate applicable construction items for the mix design.

Trial mixture information will be required by the Engineer. A trial mixture is a batch of concrete tested by the Contractor to verify the Contractor's mix design will meet specification requirements. Trial mixture information shall include test results as specified in the "Portland Cement Concrete Level III Technician" course manual. Test results shall also include slump flow, visual stability index, J-ring value, L-box blocking ratio, column segregation index, and hardened visual stability index. For the trial mixture, the slump flow shall be near the midpoint of the proposed slump flow target range.

Trial Batch. A minimum 2 cu yd (1.5 cu m) trial batch shall be produced, and the self-consolidating concrete admixture dosage proposed by the Contractor shall be used. The slump flow shall be within 1.0 in. (25 mm) of the maximum slump flow range specified by the Contractor, and the air content shall be within the top half of the allowable specification range.

The trial batch shall be scheduled a minimum of 21 calendar days prior to anticipated use and shall be performed in the presence of the Engineer.

The Contractor shall provide the labor, equipment, and materials to test the concrete. . The mixture will be evaluated by the Engineer for strength, air content, slump flow, visual stability index, J-ring value, L-box blocking ratio, column segregation index, and hardened visual stability index.

Upon review of the test data from the trial batch, the Engineer will verify or deny the use of the mix design and notify the Contractor. Verification by the Engineer will include the

Contractor's target slump flow range. If applicable, the Engineer will verify the Contractor's maximum J-ring value and minimum L-box blocking ratio.

A new trial batch will be required whenever there is a change in the source of any component material, proportions beyond normal field adjustments, dosage of the self-consolidating concrete admixture, batch sequence, mixing speed, mixing time, or as determined by the Engineer. The testing criteria for the new trial batch will be determined by the Engineer.

When necessary, the trial batches shall be disposed of accorqing to Article 202.03 of the Standard Specifications.

Mixing Portland Cement Concrete. In addition to Article 1020.11 of the Standard Specifications, the mixing time for central-mixed concrete shall not be reduced as a result of a mixer performance test. Truck-mixed or shrink-mixed concrete shall be mixed in a truck mixer for a minimum of 100 revolutions.

Wash water, if used, shall be completely discharged from the drum or container before the succeeding batch is introduced.

The batch sequence, mixing speed, and mixing time shall be appropriate to prevent cement balls and mix foaming for central-mixed, truck-mixed, and shrink-mixed concrete.

Falsework and Forms. In addition to Articles 503.05 and 503.06 of the Standard Specifications, the Contractor shall consider the fluid nature of the concrete for designing the falsework and forms. Forms shall be tight to prevent leakage of fluid concrete.

Placing and Consolidating. Concrete placement and consolidation shall be according to Article 503.07 of the Standard Specifications, except as follows:

Revise the third paragraph of Article 503.07 of the Standard Specifications to read:

"Open troughs and chutes shall extend as nearly as practicable to the point of deposit. The drop distance of concrete shall not exceed 5 ft (1.5 m). If necessary, a tremie shall be used to meet this requirement. The maximum distance of horizontal flow from the point of deposit shall be 25 ft (7.6 m), unless approved otherwise by the Engineer. For drilled shafts, free fall placement will not be permitted."

Delete the seventh, eighth, ninth, and tenth paragraphs of Article 503.07 of the Standard Specifications.

Add to the end of the eleventh paragraph of Article 503.07 of the Standard Specifications the following:

"Concrete shall be rodded with a piece of lumber, conduit, or vibrator if the material has lost its fluidity prior to placement of additional concrete. The vibrator shall be the pencil head type with a maximum diameter or width of 1 in. (25 mm). Any other method for restoring the fluidity of the concrete shall be approved by the Engineer."

Quality Control by Contractor at Plant. The specified test frequencies for aggregate gradation, aggregate moisture, air content, unit weight/yield, and temperature shall be performed as indicated in the contract plans.

Slump flow, visual stability index, and J-ring or L-box tests shall be performed as needed to control production. The column segregation-index-test and hardened visual stability index test will not be required to be performed at the plant.

Quality Control by Contractor at Jobsite. The specified test frequencies for air content, strength, and temperature shall be performed as indicated in the contract plans.

Slump flow, visual stability index, and J-ring or L-box tests shall be performed on the first two truck deliveries of the day, and every 50 cu yd (40 cu m) thereafter. The Contractor shall select either the J-ring or L-box test for jobsite testing.

The column segregation index test will not be required to be performed at the jobsite. The hardened visual stability index test shall be performed on the first truck delivery of the day, and every 300 cu yd (230 cu m) thereafter. Slump flow, visual stability index, J-ring value or L-box blocking ratio, air content, and concrete temperature shall be recorded for each hardened visual stability index test.

The Contractor shall retain all hardened visual stability index cut cylinder specimens until the Engineer notifies the Contractor that the specimens may be discarded.

If mix foaming or other potential detrimental material is observed during placement or a~ the completion of the pour, the material shall be removed while the concrete is still plastic.

Quality Assurance by Engineer at Plant. For air content and aggregate gradation, quality assurance independent sample testing and split sample testing will be performed as indicated in the contract plans .

For slump flow, visual stability index, and J-ring or L-box tests, quality assurance independent sample testing and split sample testing will be performed as determined by the Engineer.

Quality Assurance by Engineer at Jobsite. For air content and strength, quality assurance independent sample testing and split sample testing will be performed as indicated in the contract plans.

For slump flow, visual stability index, J-ring or L-box, and hardened visual stability index tests, quality assurance independent sample testing will be performed as determined by the Engineer.

For slump flow and visual stability index quality assurance split sample testing, the Engineer will perform tests at the beginning of the project on the first three tests performed by the Contractor. Thereafter, a minimum of ten percent of total tests required of the Contractor will be performed per plant, which will include a minimum of one test per mix design. The acceptable limit of preCision will be 1.5 in. (40 mm) for slump flow and a limit of precision will not apply to the visual stability index.

For the J-ring or the L-box quality assurance split sample testing, a minimum of 80 percent of the total tests required of the Contractor will be witnessed by the Engineer per plant, which will include a minimum of one witnessed test per mix design. The Engineer reserves the right to conduct quality assurance split sample testing. The acceptable limit of precision will be 1.5 in. (40mm) for the J-ring value and ten percent for the L-box blocking ratio.

For each hardened visual stability index test performed by the Contractor, the cut cylinders shall be presented to the Engineer for determination of the rating. The Engineer reserves the right to conduct quality assurance split sample testing. A limit of precision will not apply to the hardened visual stability index.

II.4 Kentucky

II.4.1 Method for Approval of Using SCC

1. SCOPE: This method covers the process for precast plants to obtain approval for use of SCC in precast products.

2. BASIC REQUIREMENTS:

2.1. Qualified manufacturers must submit a revised quality control plan utilizing SCC to the Kentucky Transportation Cabinet (KYTC) for approval, and meet all applicable requirements of the Kentucky Standard Specifications for Road and Bridge Construction
and the Prestress/Precast Manual.

3. PROCEDURES:

3.1 Submit a written request for SCC approval to: Director, Division of Materials, 1227
Wilkinson Boulevard, Frankfort, KY 40601. The request must include:

3.1.1. Mix Designs.

3.1.1.1. Minimum cementious material - 564 pounds per cubic yard.

3.1.1.2. Maximum w/c ratio of .46 (Type F or G high-range water reducer required).

3.1.1.3. Air content of 6% ± 2%

3.1.1.4. Spread limits (Indicate low end and high end of spread range)

3.1.2 SCC quality control procedures.

3.1.3 Plastic test methods and limits imposed.

3.1.4 SCC plant production records.

3.1.5 28 day strength data.

3.1.6 Core testing data, if available.

3.2 If qualified manufacturers meet the requirements set forth herein, KYTC will require a SCC demonstration for each qualifying plant. This demonstration should include representation from admixture and cement manufacturers and plant officials. A plant may receive a 90-day conditional approval if it can demonstrate a good quality mix using SCC. These approvals will be granted on a case by case basis. The KYTC will need to witness a SCC batch at the minimum and maximum spread indicated on the submitted mix designs.

3.3 During the 90-day conditional approval, KYTC will initially require that each plant provide the following:

3.3.1 Obtain 4 cores from the demonstration pours and submit them to an independent lab for air analysis in accordance with the current edition of ASTM C-457.

3.3.2 Perform and record the spread, visual rating of spread and temperature of every batch of SCC (spread test should be performed next to forms if transporting SCC by any method other than cranes) for the first 30 days of production. Provide these test results to the Division for review. This requirement may be waived for plants approved in another state using SCC for over one year.

3.4 Continue to use the approved mix design (unless additional mix designs are submitted and approved prior to use).

3.5 Maintain the spread approved by KYTC during demonstration and visually inspect for segregation and any paste outline around spread. Perform test in accordance with ASTM C-1611 and document all results.

3.6 Have a working moisture probe and compensator or KYTC approved alternative.

4. DISQUALIFICATION OF MANUFACTURERS: If the 90-day conditional approval procedures are not followed or if any problems arise that cannot be immediately corrected, the plant will be disqualified to use SCC in any KYTC product.

APPROVED
DIRECTOR
DIVISION OF MATERIALS
DATE 03/21/08
Kentucky Method 64-320-08
Revised 03/21/08
Supersedes KM 64-320-06
Dated 03/03/06

II.5 New Jersey

NJDOT's SCC Specification

http://www.state.nj.us/transportation/eng/specs/2007/spec900.shtm#s903

903.06 SELF-CONSOLIDATING CONCRETE (SCC)

903.06.01 SCC for Drilled Shafts

A. **Composition.** Produce SCC conforming to the composition requirements specified in 903.03.01, except use a Type F admixture and a viscosity modifying admixture (VMA). Use Type F and VMA admixtures, as specified in 903.02.02 and 903.02.04, at a dosage to produce a flowable concrete that does not require vibration for consolidation. Proportion the aggregates so that the fine aggregate is less than 50 percent by weight of the total aggregate.

B. **Mix Design and Verification.** Design the mix as specified in 903.03.02 to conform to the strength requirements, water-cement ratio, and cement content for a Class A concrete and the requirements specified in Table 903.06.01-1, Table II.4

Table AII.4: Requirements for SCC for drilled shafts

Table 903.06.01-1 Requirements for SCC for Drilled Shafts		
Property	**Test Method**	**Requirement**
Air Content		
Coarse Aggregate No. 57	AASHTO T 152	6.5 ± 2.0 percent
Coarse Aggregate No. 67		6.5 ± 2.0 percent
Coarse Aggregate No. 8		7.5 ± 2.0 percent
Slump Flow	NJDOT C-4	21 ± 3 inches
Visual Stability Index		
Plastic Concrete	NJDOT C-4	1 maximum
Hardened Concrete	NJDOT C-5	1 maximum

C.

Perform mix design verification as specified in 903.03.02. For the verification batch, ensure that the air content is in the top half of the allowable range and the slump flow is between 21 and 24 inches. Perform air content, slump flow, and visual stability index (plastic concrete) testing on the verification batch. Make concrete cylinders for compression testing as specified in 903.03.02 and make 2 additional 4 × 8-inch cylinders for evaluation of the visual stability index of the hardened concrete. Saw the additional cylinders length-wise according to NJDOT C-5. The ME will perform the compressive strength testing and the visual evaluation to assign a visual stability index in order to approve the mix.

D. **Verification of Pumpability.** Verify pumpability at least 10 days before pouring the SCC concrete in the drilled shaft. Demonstrate the pumpability of the SCC to the ME by pumping a trial batch through the pump proposed for placing the SCC into the drilled shaft. Use the proposed methods for mixing the concrete including any anticipated time delays. The ME will test the SCC before and after pumping to verify that the SCC meets the requirements of Table 903.06.01-1 after pumping.

E. **Mixing.** Mix SCC as specified in 903.03.03.

F. **Control and Acceptance Testing.** Perform quality control testing as specified in 903.03.05.

The ME will perform acceptance testing as specified in 903.03.05 for a non-pay adjustment Class A concrete, except that the provisions for slump testing are replaced with requirements for slump flow testing and visual stability index on the plastic concrete. The ME will perform the slump flow testing and the visual stability index according to NJDOT C-4, at the sampling rate specified for slump testing of Class A concrete. The ME will perform visual stability index on the hardened concrete according to NJDOT C-5 at a rate of at least 1 per day. If the visual stability index on the hardened concrete does not conform to the criteria in Table 903.06.01-1, the ME will require redesign of the mix.

In the performance of quality control or acceptance testing, fill cylinder molds, slump flow cones, and air buckets in one lift. Do not vibrate, rod, or tap to consolidate the SCC.

903.06.02 SCC For Precast Concrete

A. **Composition.** Produce SCC conforming to the composition requirements specified in 903.03.01, except use a Type F admixture or a combination of a Type F and a viscosity modifying admixture (VMA). Use Type F and VMA admixtures, as specified in 903.02.02 and 903.02.04, at a dosage to produce a flowable concrete that does not require vibration for consolidation. Proportion the aggregates so that the fine aggregate is less than 50 percent by weight of the total aggregate.

B. **Mix Design and Verification.** Design the mix, as specified in 903.03.02 or 903.05.02, to conform to the strength, water-cement ratio, cement content, and air content requirements for the specified class of concrete for the item that is being cast. In addition, ensure that the SCC conforms to the requirements specified in Table 903.06.02-1, Table II.5

Table AII.5: Requirements for SCC for precast concrete

Table 903.06.02-1 Requirements for SCC for Precast Concrete		
Property	Test Method	Requirement
Slump Flow	NJDOT C-4	24 to 28 inches
Visual Stability Index		
Plastic Concrete	NJDOT C-4	1 maximum
Hardened Concrete	NJDOT C-5	1 maximum

C. Perform mix design verification as specified in 903.03.02 or 903.05.02. For the verification batch, ensure that the air content is in the top half of the allowable range and the slump flow is between 26 and 28 inches. Perform air content, slump flow, and visual stability index (plastic concrete) testing on the verification batch. Make concrete cylinders for compression testing as specified in 903.03.02 or 903.05.02 and make 2 additional 4 × 8 inch cylinders for visual stability index on the hardened concrete. Saw the additional cylinders length-wise according to NJDOT C-5. The ME will perform the compressive strength testing and the visual evaluation to assign a visual stability index in order to approve the mix.

D. **Mixing.** Mix SCC as specified in 903.03.03.

E. **Control and Acceptance Testing.** Perform quality control testing as specified in 903.03.05.

The ME will perform acceptance testing as specified in 903.03.05 for specified class of concrete for the item, except that the provisions for slump testing are replaced with requirements for slump flow testing and visual stability index on the plastic concrete.

The ME will perform the slump flow testing and the visual stability index according to NJDOT C-4, at the sampling rate specified for slump testing for the specified class of concrete. The ME will perform visual stability index on the hardened concrete according to NJDOT C-5 at a rate of at least one per day. If the visual stability index on the hardened concrete does not conform to the criteria specified in Table 903.06.02-1, the ME will require redesign of the mix.

In the performance of quality control or acceptance testing, without remixing the sample, fill cylinder molds, slump flow cones, and air buckets in one lift. Do not vibrate, rod, or tap to consolidate the SCC.

II.6 New York

New York DOT's Optional SCC Note V3

Optional Self Compacting Concrete for Removal and Replacement of Structural Concrete

The contractor may, with the approval of the Engineer, submit a proposed mix design for Self Consolidating Concrete (SCC). This mix may be used under the Materials Requirements for Item 582-Removal and Replacement of Structural Concrete. All cost shall be included in the bid price for Items 582.05 or 582.06 and all necessary materials, labor, and equipment shall be provided at no additional cost to the state. Use of a Corrosion Inhibiting Admixture in SCC will be as required by the plans and proposal and paid under a separate specification.

Under this option, the contractor will create a mix design, and prepare a trial batch using those materials to be used on the project. The contractor must demonstrate the mix's ability to achieve the specified properties to the Regional Materials Engineer's satisfaction. At least three weeks prior to placement, the contractor shall supply:

- Mix design and compressive strength results, including rate of strength gain for 1, 3, 7, 14, and 28 days, or maturity curves with corresponding temperatures as appropriate.

- Proposed target limits for spread, indicating acceptable low and high spread limits and proposed actions when mixture testing is outside of the target limits.
- Proposed visual stability index (VSI) allowable measurements for acceptance.
- Air content.

The contractor will provide a proposed quality control plan, including how the above performance criteria will be maintained and actions taken when test results are not acceptable. Once a mixture design is accepted by the Department, changes other than minor fluctuations in admixture dosage rates will require a new mix design.
All other provision of Item 582 apply, unless otherwise directed by the Engineer.

II.7 South Dakota

SDDOT's specifications book online:
http://www.sddot.com/Operations/specifications/index2004.htm

II.7.1 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: Course aggregate for SCC shall meet the requirements of Section 820 with the following exceptions:

Course 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 course 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 course aggregate shall be tested at the same frequency as the course 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 Course Aggregate Content:** The SCC shall consist of a minimum course 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.

II.8 Virginia

II.8.1 **ROUGH DRAFT- 08/19/05**

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
SELF-CONSOLIDATING CONCRETE (SCC) FOR USE IN REPAIRS
August 19, 2005

I. DESCRIPTION

This work shall consist of designing and furnishing a self- consolidating concrete mix design for use in the repair of concrete structural elements. The Contractor shall perform structural repairs in accordance with applicable sections of the Specifications and the specifications herein.

II MATERIALS

Material components for self-consolidating concrete use in repairs shall conform to the following:

A. **Cement**: Portland Type I/II

B. **Class F and N fly ash or slag** conforming to the requirements of ASTM C618 and ASTM C 989, Grade 100 or 120 respectively

C. **Coarse Aggregate** conforming to the requirements of ASTM C33. Maximum size of aggregates to meet project requirements.

D. **Fine Aggregate** shall conform to the requirements of ASTM C33

E. **Water** shall be potable. Otherwise must be approved by the Engineer before use.

F. **Air entraining admixtures** shall conform to the requirements of ASTM 260

G. **Water reducing, retarding or accelerating admixtures** shall conform to the requirements of ASTM C494.

H. **High-range water-reducing admixtures** (HRWR) or (super plasticizers) shall conform to the requirements of ASTM C494 Type F or G or ASTM C1017.

I. **Viscosity modifying admixtures** can be used to attain desired stability and flow characteristics, if all other specified properties are met (approved by the Engineer).

J. **Fibers** – Synthetic fibers shall conform to the requirements of ASTM C1116 and can be used to control cracking

K. **Shrinkage-reducing admixtures,** as approved by the Engineer, may be added to control cracking

L. **Forming Materials**: Forming material shall be steel, steel framed plywood, resin impregnated plywood, plastic or paper faced plywood, or other material, all to be approved by the Engineer. Form shall not have voids or cracks that would permit the flow of concrete and shall be strong enough to stand the form pressures.

III. CONCRETE REQUIREMENTS

A qualified SCC technologist shall design and determine the proportioning of mixes since there is no standardized SCC mix design method. Experienced admixtures' suppliers can also be of assistance in determining mix design for project requirements. The following characteristics are very important for successful application of SCC and must be conformed to by the Contractor's mix design:

Flowability (Filling Ability) - ability of SCC to fill the forms and consolidate without vibration.

Stability- (segregation resistance) – ability of SCC to remain homogeneous during transport, placement and subsequent to placement.

Passing ability – ability of SCC to flow through reinforcement without aggregate blocking the flow.

Maximum water-cementitious materials ratio: 0.45

Air content **-** 7$\pm$2%

Slump-flow **-** 25 to 28 inches

Compressive Strength **-** Minimum 28-day - 3,000 psi minimum, 7,000 psi maximum. Loading carrying sections shall have a minimum of 3,000 psi compressive strength before opening to traffic.

Shrinkage - 0.04% or less at 28 days.

IV. QUALIFIED SCC TECHNOLOGIST

The Contractor shall employ the services of a qualified SCC Technologist, who is a person with experience in proportioning, batching, testing, and placing SCC. The

Engineer, based upon a resume submitted to the Engineer, shall approve the SCC Technologist.

V. CONCRETE TESTS (subject to change)

1. Slump-flow: To determine flowability and segregation: Conducted by a standard slump cone (either upright or inverted cone) and placed on a nonabsorbent smooth surface. It is filled in 1 lift without consolidation. It is pulled in an upward motion at a speed not causing a break in the flow. The concrete should flow into a consistent circle. The diameter of the spread is measured at two perpendicular points and an average is taken to give slump flow in inches. At this time it should be checked visually to ensure that there is no evidence of segregation in the concrete spread, no ring of mortar halo around the spread, or aggregate pile in the spread.
2. J-Ring: To determine the passing ability: A J-Ring will be placed on the base plate. For a nominal maximum aggregate size of 1-in, J-Ring shall have 16 stainless steel rods with ½ in diameter spaced equally in a circle having a radius of 12 in. The slump cone will be placed in the middle of the J-Ring either upright or inverted. If upright, the handles of the slump cone may need to be removed to fit inside the J-Ring. The slump flow with the J-Ring and the difference in height between the SCC inside and that just outside the J-Ring will be measured.
3. Air content: Freshly mixed concrete by the pressure method, ASTM C231, or the volumetric method, ASTM C173.
4. Strength at 7 and/or 28 days: ASTM C39
5. Shrinkage: ASTM C 157 (28 days air dried at 50$\pm$4% RH)
6. Permeability at 28 days after 1 week of moist curing at 73F and 3 weeks at 100F: ASTM C1202
7. Specimens shall be prepared by filling the molds in one lift without any consolidation.

VI. SURFACE PREPARATION

Remove the deteriorated concrete and soak the prepared surface to a SSD condition.

Also, immediately before concrete placement, thoroughly wet moisture-absorbing material that will be in contact with concrete. There shall be no standing water at time of concrete placement.

Adequate anchors for fixing wire mesh or reinforcement for mechanically anchoring SCC shall be provide Immediately before concrete placement, thoroughly wet moisture-absorbing material that will be in contact with concrete.

VII. CONCRETE PLACEMENT AND CONSOLIDATION

A concrete technologist (such as the admixture supplier) experienced in the production of SCC representing the Contractor or the concrete producer shall be present during placement.

Concrete shall stay plastic and within the slump flow specified during the placement.

Any extended delay that allows the preceding load to lose flow and not combine with the next load is unacceptable and will be cause for rejection.

Ready mix concrete producer shall supply concrete in such a manner as to provide continual placement of concrete.

Concrete shall be poured from one side to the other or pumped from the bottom upward so as not to encapsulate air.

If finishing work is necessary, the exterior face of exterior surfaces shall be finished free from blemishes and then rubbed with burlap.

VIII. FINISH

Final surface shall have a smooth finish without large holes (larger than 3/8 inch) and without sand streaks except as may be required by project requirements.

II. DESCRIPTION

This work shall consist of designing and furnishing a self- consolidating concrete mix design for the construction of prestressed concrete bridge beams. The Contractor shall construct the bridge beams in accordance with applicable sections of the Specifications and the specifications herein.

II MATERIALS

Material components for self-consolidating concrete shall conform to the following:

A. **Cement**: Portland Type I, II, I/II, or III

B. **Class F and N fly ash or slag** conforming to the requirements of ASTM C618 and ASTM C 989, Grade 100 or 120 respectively

C. **Coarse Aggregate** conforming to the requirements of ASTM C33. Maximum size of aggregates to meet project requirements.

D. **Fine Aggregate** shall conform to the requirements of ASTM C33

E. **Water** shall be potable. Otherwise must be approved by the Engineer before use.

F. **Air entraining admixtures** shall conform to the requirements of ASTM 260

M. **Water reducing, retarding or accelerating** admixtures shall conform to the requirements of ASTM C494.

N. **High-range water-reducing admixtures** (HRWR) or (super plasticizers) shall conform to the requirements of ASTM C494 Type F or G or ASTM C1017.

I. **Viscosity modifying admixtures** can be used to attain desired stability and flow characteristics, if all other specified properties are met (approved by the Engineer).

J. **Forming Materials**: Forming material shall be steel, steel framed plywood, resin impregnated plywood, plastic or paper faced plywood, or other material, all to be approved by the Engineer. Form shall not have voids or cracks that would permit the flow of concrete and shall be strong enough to stand the form pressures.

III. CONCRETE REQUIREMENTS

A qualified SCC technologist shall design and determine the proportioning of mixes since there is no standardized SCC mix design method. Experienced admixtures' suppliers can also be of assistance in determining mix design for project requirements. The following characteristics are very important for successful application of SCC and must be conformed to by the Contractor’s mix design:

Flowability (Filling Ability) - ability of SCC to fill the forms and consolidate without vibration.

Stability- (segregation resistance) – ability of SCC to remain homogeneous during transport, placement and subsequent to placement

Passing ability – ability of SCC to flow through reinforcement without aggregate blocking the flow.

Maximum water-cementitious materials ratio: 0.40

***Air content* -** 5.5±1.5%

***Slump-flow* -** 23 to 28 inches

The difference between the slump flow with and without the J-Ring shall be within 1 in of each other. The slump flow may be measured with the slump cone in either upright or inverted position. The difference in height between the SCC inside and that just outside the J-Ring shall be less than ½ inch.

***Compressive Strength* -** Minimum 28-day 5,000 psi. For design values of 8,000 psi to 10,000 psi, permission of the State Structure and Bridge Engineer is required.

***Permeability* -** Maximum 28-day 1,500 coulombs.

Shrinkage - 0.04% or less at 28 days.

IV. QUALIFIED SCC TECHNOLOGIST

The Contractor shall employ the services of a qualified SCC Technologist, who is a person with experience in proportioning, batching, testing, and placing SCC. The Engineer, based upon a resume submitted to the Engineer, shall approve the SCC Technologist.

V. CONCRETE TESTS

1. Slump-flow: To determine flowability and segregation: Conducted by a standard slump cone (either upright or inverted cone) and placed on a nonabsorbent smooth surface. It is filled in 1 lift without consolidation. It is pulled in an upward motion at a speed not causing a break in the flow. The concrete should flow into a consistent circle. The diameter of the spread is measured at two perpendicular points and an average is taken to give slump flow in inches. At this time it should be checked visually to ensure that there is no evidence of segregation in the concrete spread, no ring of mortar halo around the spread, or aggregate pile in the spread.

2. J-Ring: To determine the passing ability: A J-Ring will be placed on the base plate. For a nominal maximum aggregate size of 1-in, J-Ring shall have 16 stainless steel rods with ½ in diameter spaced equally in a circle having a radius of 12 in. The slump cone will be placed in the middle of the J-Ring either upright or inverted. If upright, the handles of the slump cone may need to be removed to fit inside the J-Ring. The slump flow with the J-Ring and the difference in height between the SCC inside and that just outside the J-Ring will be measured.
3. Air content: Freshly mixed concrete by the pressure method, ASTM C231, or the volumetric method, ASTM C173.
4. Strength at 7 and/or 28 days: ASTM C39
5. Shrinkage: ASTM C 157 (28 days air dried at 50±4% RH)
6. Permeability at 28 days after 1 week of moist curing at 73F and 3 weeks at 100F: ASTM C1202
7. Specimens shall be prepared by filling the molds in one lift without any consolidation.

VI. SURFACE PREPARATION

Immediately before concrete placement, thoroughly wet moisture-absorbing material that will be in contact with concrete. There shall be no standing water at the time of concrete placement.

VII. CONCRETE PLACEMENT AND CONSOLIDATION

A concrete technologist (such as the admixture supplier) experienced in the production of SCC representing the Contractor or the concrete producer shall be present during placement.

Concrete shall stay plastic and within the slump flow specified during the placement. Any extended delay that allows the preceding load to lose flow and not combine with the next load is unacceptable and will be cause for rejection.

Concrete shall be poured from one side to the other or pumped from the bottom upward so as not to encapsulate air.

If finishing work is necessary, the exterior face of exterior beams shall be finished free from blemishes and then rubbed with burlap.

IX. FINISH

Final surface shall have a smooth finish without large holes (larger than 3/8 inch) and without sand streaks except as may be required by project requirements.

II.9 Washington

WSDOT Standard Specifications (M 41-10)

Available at:

http://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/SS2008.pdf

II.9.1 Washington's BSP for the Tacoma Narrows noise walls & Fredonia test shafts

Self Consolidating Concrete

Concrete shall be self consolidating concrete.

The self consolidating concrete mix shall include set retarding and water reducing admixtures conforming to Section 9-23.6. The use of viscosity modifying admixtures (VMA) is permitted.

Aggregates shall conform to Section 9-03.1.

The Contractor shall submit the mix design for the self consolidating concrete to be used to the Engineer for approval, using WSDOT Form 350-040. The Contractor shall submit the mix design submittal to the Engineer at least 30 calendar days prior to the beginning noise barrier wall construction operations.

The mix design submittal shall include the mix proportions per cubic yard, the proposed material sources, the fineness modulus, the water / cement ratio, air content and the aggregate correction factor in accordance with WAQTC FOP for AASHTO T 152.

The mix design submittal shall include laboratory test results based on the following performance criteria and shall include the following information:

1. Unit weight in pounds per cubic foot in accordance with AASHTO T 121.
2. Concrete temperature in accordance with Section 6-02.3(4)D.
3. Slump flow in the range of 22 to 29 inches with a maximum visual stability index (VSI) of 1 in accordance with ASTM C 1611 /C 1611M.
4. J ring test results in accordance with ASTM C 1621/C 1621M., meeting a blocking assessment of less than 2 inches.
5. Test results for flow rate T20, defined as the time it takes for the outer edge of 11 the concrete mass to reach a diameter of 20 inches, shall be less than 6 seconds.
6. Column segregation test results in accordance with ASTM C 1610 with a maximum index of 10 percent.
7. 28 day compressive strength of 4,000 psi minimum, in accordance with AASHTO T 23.

The self consolidating concrete shall be capable of being pumped and capable of flowing through the wall steel reinforcing bar cage without segregation or buildup of any differential head inside or outside the cage.

A.III: NDOR Guide for Use of SCC in Special Applications

III.1 Scope

This Guide specifies the procedures for using special cast-in-place applications of self-consolidating concrete (SCC). These procedures are based on the experience gained from laboratory and full-scale tests.

SCC must have an adequate flowing ability, segregation resistance during and after placing of concrete, and filling ability through dense reinforcement and around other obstacles such as recesses and embedded items.

III.2 Material Property Requirements

The SCC mix design satisfies the following requirements specified by the Nebraska Department of Roads (NDOR):

Table AIII.1: NDOR requirements

Base Cement Type[1]	Portland Cement (Min. lb/cy)	Pre-Blended Class F Fly Ash (Min. lb/cy)[1]	Total Cementitious Materials (Min. lb/cy)	Proportion of Fine Agg. To Total Agg. (% by wt.)[2]	Type of Coarse Agg.	Air Content (% Min.)[3]	Water/ Cementitious Ratio (Max.)	28-Day Required Strength (Min. psi)
1PF	607	203	810	75 $^{+}$/- 3	Limestone	6.0	0.37	6000

(1) Mixes with Type 1PF and Class F fly ash designation are pre-blended or interground with Class F fly ash by the cement mill producer at a rate of 25%±2%. No additional Class F fly ash will be added at the batch plant. Type 1PF cement shall meet all requirements of ASTM C 595

(2) Aggregates shall meet Section 1033 of the Standard Specifications except for the gradation of the aggregate.

(3) As determined by ASTM C 173, "Air Content of Freshly Mixed Concrete by the Volumetric Method"

Material requirements

- Maximum nominal aggregate size is 3/4 inch (this provides a minimum clear cover of 3/4 inch).
- Mix must retain SCC properties for up to 90 minutes based on ASTM C 1611 Slump Flow Test, Visual Stability Index (found in Appendix of ASTM 1611), and ASTM 1621 J-Ring method.

- Achieve pumpability up to 250 ft. without causing segregation based on Visual Stability Index described in the appendix of ASTM 1611.

III.3 Materials

According to the NDOR recommendation, 1PF cement (Type I/II cement pre-blended with 25% +/- 2% of Class F fly ash) is required for use with locally available aggregates. Examples of gradation curves used during the experimental in field trial are shown in Tables III.2 and III.3.

Table AIII.2: Course Aggregate Gradation

Percent Passing		
Sieve Size	Target Value	Tolerance
1½ inch	100	None
1 inch	100	None
¾ inch	100	None
½ inch	75	± 5
3/8 inch	30	± 15
# 4	6	± 6
#10	---	---
#20	2*	± 2
#200	1.5	± 1.5
* The precent passing may be increased to 3±3 provided no more than 1.5% is passing the #200 sieve when washed.		

Table AIII.3: Fine Aggregate Gradation

Percent Passing		
Sieve Size	Target Value	Tolerance
1 inch	100	None
3/8 inch	---	---
# 4	87	± 10
#10	60	± 10
#20	28	± 12
#200	1.5	± 1.5

III.4 SCC Mix Design

The recommended mix design is given in Table III.4:

Table AIII.4: SCC Mix Design (per cubic yard)

Item	Weight $\frac{lb}{cy}$	Admixtures
I PF Cement	810	
Course Aggregate (Limestone)	702	
Fine Aggregate (Sand and Gravel)	2088	
Water	297	
Pav Air 90	0.2	3.2
*Type B Retarder	3.6	57.6
** Type F High Range Water Reducer (HRWR)	6	96
***Viscosity Modifying Admixture	2.7	43.2

Note: All admixtures will be determined by the ready mix plant and will meet NDOR specifications. Below is the list of products which were used during the research that was conducted in order to develop this user guide:

* Delvo Stabilizer

** Glenium 3030

** Rheomac VMA 362

It is recommended that concrete be mixed with 2/3 of the required amount of HRWR at the plant. The VMA and the remaining 1/3 of HRWR should be added on site just before casting.

III.5 Forms and Molds

All common materials can be used for form surfaces. With regard to surface pores, wood is found to perform better than plywood, and plywood is better than steel.

When using a mold release agent on the surfaces, let the surfaces dry completely, as any release agent left on the mold will cause pores to develop. A vegetable-oil-based release agent will perform better than oil-based petroleum products. When using formwork with smooth surfaces, the best surface quality is obtained without using any mold release agent, especially when a new plywood or wood form is used. When the form's skin is colder than the SCC, more pores will develop on the surface.

During winter conditions, when temperatures are less than +40 ºF (5 ºC), it may be necessary to use thermal insulation (outside the formwork) to maintain the temperature and normal setting time of concrete, as SCC is more sensitive than traditional vibrated concrete to low temperatures during the hardening process.

When placing concrete for a wall, a better surface can be obtained by using a tube connected to the bottom of the formwork rather than casting from above. Also, keeping the opening of the hose from the concrete pump under the surface of the fresh concrete can result in a better surface on the hardened concrete.

Because of the additional pressure that SCC places on formwork, as compared to traditional concrete, the formwork must be designed to account for hydrostatic pressure. The forms must be rigid enough to maintain the weight of the flowable concrete and withstand all lateral pressure. The form joints shall also be sealed to prevent any leakage that could occur with SCC.

III.6 Transportation

SCC must be transported to the construction site by agitating mixer trucks. On site, SCC can be delivered using a concrete pump, or chute.

SCC can segregate if it is not agitated properly during transport and waiting time. Mixer trucks must be checked to ensure they are suitable for this purpose prior to use. The truck driver must check the concrete drum before filling it with SCC to make sure that the drum is clean and moist but without free water. During transport to the site and the waiting time, the drum must rotate at low speed (not less than 1 rotation per minute). However, just before delivery at the construction site, the drum must be rotated at full speed (10-20 rotations per minute) for at least 3 minutes prior to placement. Extra care is required for long deliveries.

Before the SCC is poured on site, it must be checked using the Visual Stability Index and Slump flow test (see ASTM 1611) to verify the material's workability and make sure that there is no sign of segregation.

III.7 Placement

Before starting to use SCC on site, the personnel must be informed of its special requirements. After gaining some experience with SCC, it is recommended that the results be discussed and evaluated.

The flowchart for suggested placement of SCC which was utilized in the research field trial conducted to develop this user guide is shown in Figure 3. The tests that are required by NDOR to verify that delivered SCC retains the necessary material properties upon delivery are the Slump Flow test (ASTM 1611), Visual Stability Index test (ASTM 1611Appendix), and the J-Ring (ASTM 1621). If the consistency is acceptable according to NDOR specifications and there is no sign of segregation, the concrete can be placed.

SCC can be delivered by pump, skip, or chute. Infield research trials proved that SCC can be successfully pumped the required 250 ft which was evaluated during the investigation.

If there is an unintended interruption during casting and the concrete mix starts to harden, it may be necessary to “wake up” the placed concrete before resuming the casting operation. This can be accomplished by striking a stick or a board into the concrete several times.

It is difficult to obtain a sloped surface grater that 2% using SCC. If possible traditional concrete should be considered when these slopes are specified.
Reducing the SCC slump flow may help to achieve slopes greater than 2% using SCC, however this is an issue that must be taken into account when developing the mix design.

When there are different levels within the area to be cast, problems may arise. One solution is to erect a form with a floating surface panel for the part including the raised area. Then, the lower part is cast and left for some time until it has started to stiffen; and after that, it is possible to finish placing the concrete. Another way to handle this problem is, if possible, to use traditional vibrated concrete for the slopes or raised areas.

Large amounts of admixtures are necessary when casting in cooler weather, concrete will experience a longer initial set time. The opposite will be true for normal ambient temperatures due to the amount of fines in the SCC mix design. Once the admixtures begin to wear off, traditional vibrating might be necessary.

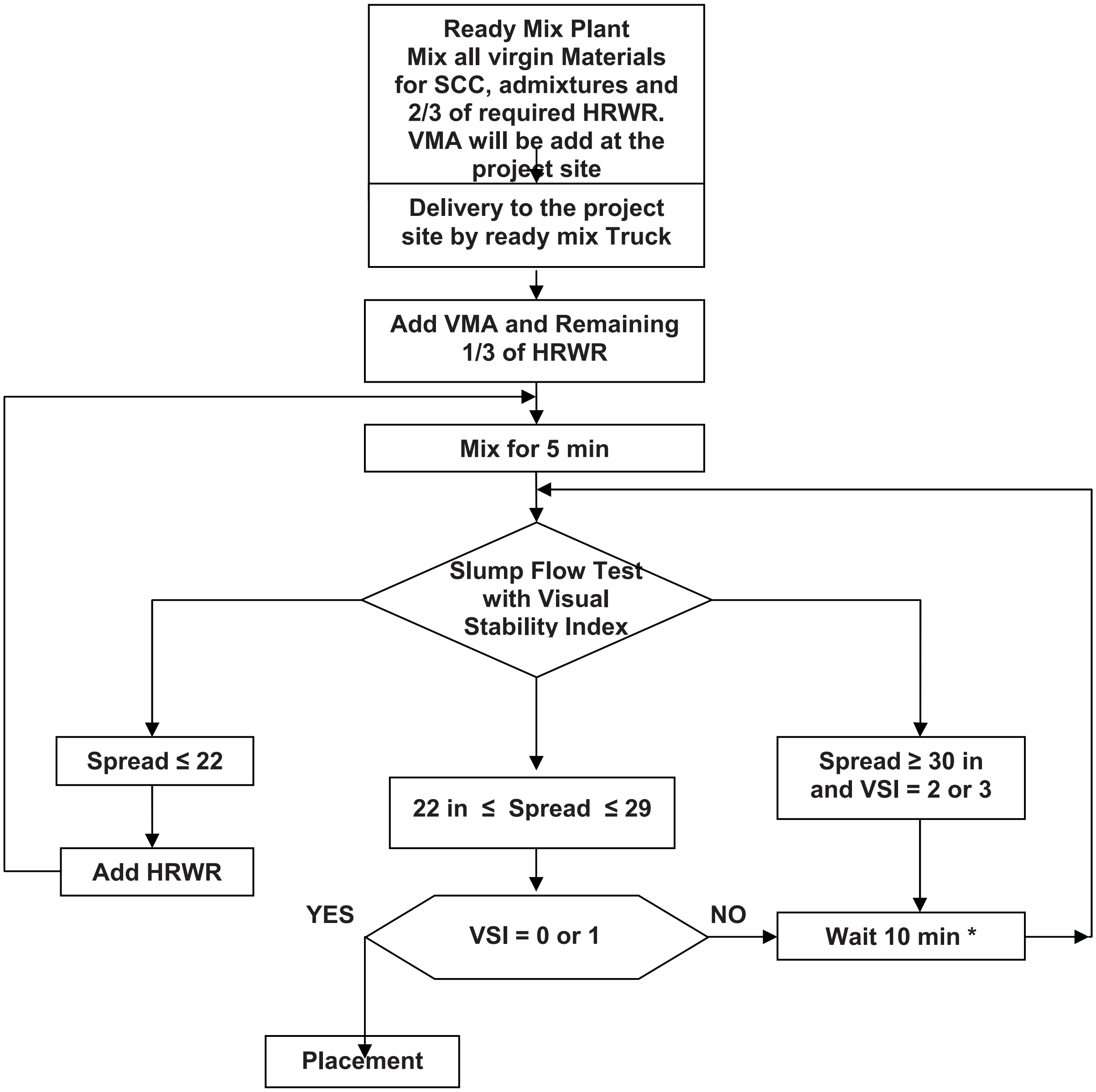


Figure AIII.1. Suggested procedure for placing on site

* If VSI is 2 or 3 after 20 min, the concrete mix can be unacceptable for structural applications. 8.Quality Control

Ready Mix plant shall be pre-approved by NDOR before any SCC is produced for a state project, by any ready mix plant. In addition to normal testing, the following tests are useful during the development, production and quality control for the use of SCC.

- Slump flow ASTM 1611
- T-50 ASTM 1611
- J-Ring ASTM 1621
- Visual Stability Index Appendix of ASTM 1611

- Air Content, Pressure Method ASTM 173

For a given mix, it is recommended that upper limits are set on the Slump Flow test and the T50. The Slump Flow test and the T50 are still the best methods to determine the filling ability for fresh concrete properties at least on the construction site, but they are not sufficient by themselves to determine if the concrete is segregation resistant.

The slump flow test shall be used for comparison with the target value from the mix design but can also be used by experienced personnel to indicate the quality of the concrete with respect to segregation, separation, etc.

AIV: American Petrographic Services Original Testing Results

IV.1 Air Void Analysis

Trial 2: NC:6.5:0.0FA

Trial 5:SCC:6.5:0.0FA

Trial 15: SCC:6.5:30FA

Trial 25: NC:6.0:30FA

Trial 22: NC:6.5:30FA

Trial 18: SCC:6.0:FA

American Petrographic Services, Inc.

AIR VOID ANALYSIS

PROJECT:
LINEAR TRAVERSE SAMPLES

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
3701 CAMPUS ROAD STOP 7053
GRAND FORKS, ND 58202

ATTN: JOE TONNESEN

APS JOB NO: 10-05734

DATE: JANUARY 16, 2009

Sample ID: Trial 4

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

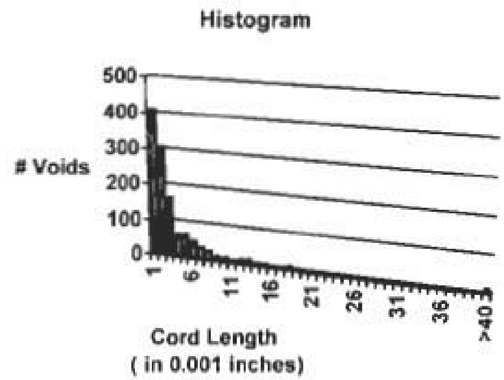
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

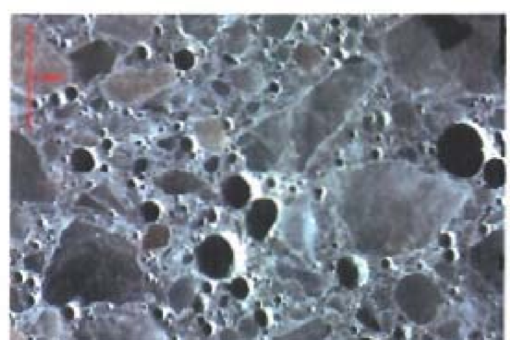
Air Void Content %	5.7
Entrained, % ≤ 0.040"	4.7
Entrapped, %> 0.040"	1.0
Air Voids/inch	13.42
Specific Surface, in2/in3	950
Spacing Factor, inches	0.005
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	90
Test Date	01/16/2009



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024



Magnification: 30x
Description: Overall hardened air content, 5.7% total

American Petrographic Services, Inc.

AIR VOID ANALYSIS

PROJECT:
LINEAR TRAVERSE SAMPLES

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
3701 CAMPUS ROAD STOP 7053
GRAND FORKS, ND 58202

ATTN: JOE TONNESEN

APS JOB NO: 10-05734

DATE: JANUARY 19, 2009

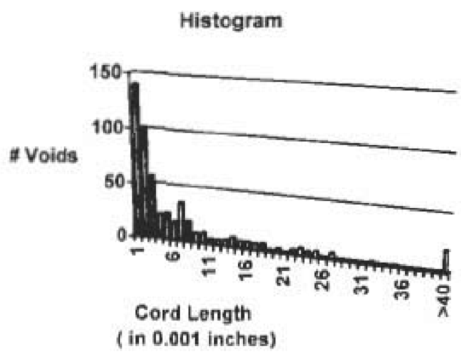
Sample ID: Trial 9

Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.

Sample Data:
Description: Hardened Concrete Cylinder
Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

Air Void Content %	5.0
Entrained, % ≤ 0.040"	3.4
Entrapped, %> 0.040"	1.6
Air Voids/inch	5.97
Specific Surface, in2/in3	480
Spacing Factor, inches	0.010
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	90
Test Date	01/19/2009



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024

Magnification: 30x
Description: Overall hardened air content, 5.0% total

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American Petrographic Services, Inc.

AIR VOID ANALYSIS

PROJECT:
LINEAR TRAVERSE SAMPLES

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
3701 CAMPUS ROAD STOP 7053
GRAND FORKS, ND 58202

ATTN: JOE TONNESEN

APS JOB NO: 10-05734

DATE: 01/19/2009

Sample ID: T23

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

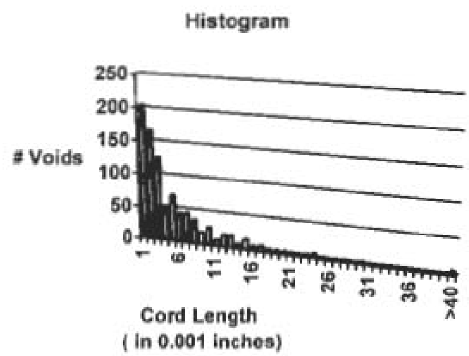
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

Air Void Content %	5.4
Entrained, % ≤ 0.040"	5.1
Entrapped, %> 0.040"	0.3
Air Voids/inch	9.89
Specific Surface, in2/in3	730
Spacing Factor, inches	0.006
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	90
Test Date	01/19/2009



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
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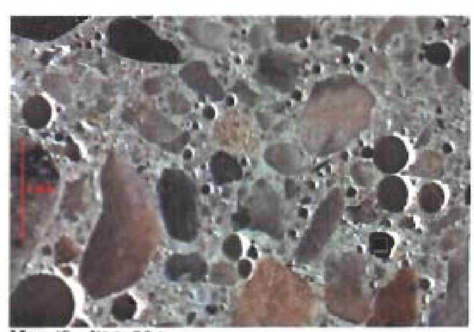
MN License #30024



Magnification: 30x
Description: Overall hardened air content, 5.4% total

American Petrographic Services, Inc.

AIR VOID ANALYSIS

PROJECT:
LINEAR TRAVERSE SAMPLES

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
3701 CAMPUS ROAD STOP 7053
GRAND FORKS, ND 58202

ATTN: JOE TONNESEN

APS JOB NO: 10-05734

DATE: JANUARY 19, 2009

Sample ID: T34

Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

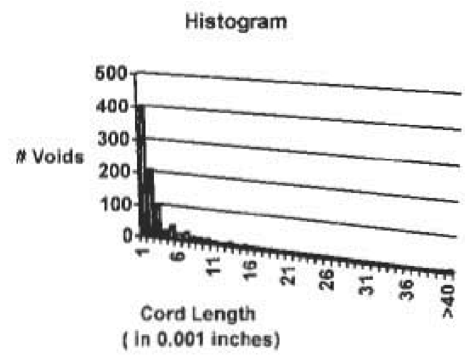
Sample Data:

Description: Hardened Concrete Cylinder

Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

Air Void Content %	3.5
Entrained, % ≤ 0.040"	3.2
Entrapped, %> 0.040"	0.3
Air Voids/inch	9.99
Specific Surface, in2/in3	1140
Spacing Factor, inches	0.005
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	90
Test Date	01/19/2009



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024

Magnification: 30x
Description: Overall hardened air content, 3.5% total

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3701 CAMPUS ROAD STOP 7053
GRAND FORKS, ND 58202

ATTN: JOE TONNESEN
DATE: JANUARY 19, 2009

APS JOB NO: 10-05734

Sample ID: T31

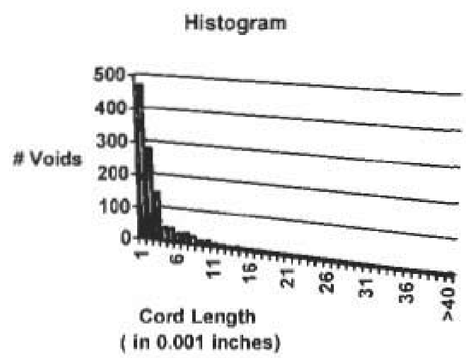
Conformance: The sample contains an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data:

Description: Hardened Concrete Cylinder
Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

Air Void Content %	4.6
Entrained, % ≤ 0.040"	4.0
Entrapped, %> 0.040"	0.6
Air Voids/inch	12.61
Specific Surface, in2/in3	1090
Spacing Factor, inches	0.005
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	90
Test Date	01/19/2009



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.

Report Prepared By:

Scott Wolter, PG
President
MN License #30024

Magnification: 30x
Description: Overall hardened air content, 4.6% total

AIR VOID ANALYSIS

American Petrographic Services, Inc.

PROJECT:
LINEAR TRAVERSE SAMPLES

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
3701 CAMPUS ROAD STOP 7053
GRAND FORKS, ND 58202

ATTN: JOE TONNESEN
DATE: JANUARY 19, 2009

APS JOB NO: 10-05734

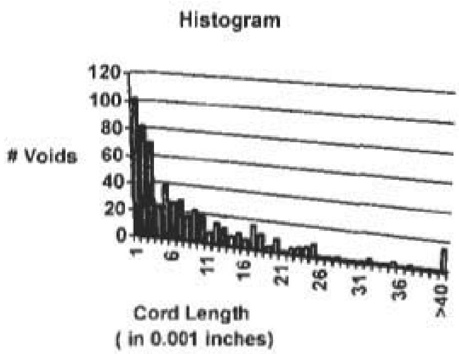
Sample ID: T27

Conformance: The sample contains an air void system which is not consistent with current technology for freeze-thaw resistance.

Sample Data:
Description: Hardened Concrete Cylinder
Dimensions: 102 mm (4") diameter x 203 mm (8") long

Test Data: ASTM:C457 Linear Traverse Method, APS SOP 00LAB003 and ACI 116R

Air Void Content %	5.8
Entrained, % ≤ 0.040"	4.8
Entrapped, %> 0.040"	1.0
Air Voids/inch	6.54
Specific Surface, in2/in3	450
Spacing Factor, inches	0.010
Paste Content, % estimated	26.0
Magnification	50x
Traverse Length, inches	90
Test Date	01/16/2009



The test sample will be retained for at least 30 days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. Test results relate only to the item tested.
Report Prepared By:

Scott Wolter, PG
President
MN License #30024

Magnification: 30x
Description: Overall hardened air content, 5.8% total

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AVIII.2 American Petrographic Services Permeability Results

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT: EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT	**REPORTED TO:** UNIVERSITY OF NORTH DAKOTA DEPARTMENT OF CIVIL ENGINEERING UPSON II ROOM 260 243 CENTENNIAL DRIVE STOP 8115 GRAND FORKS, ND 58202-8115 **ATTN:** JOE TONNESON
APS JOB NO: 10-05752	**DATE:** JANUARY 29, 2009

Sample No:	SCC 6.0 30 FA
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 52 mm (2-1/16") long
Date Cast:	November 26, 2008
Date Tested:	January 28, 2009
Age:	63 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1630	97.8
Average	1630	97.8

CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

Megan Koch
Petrographer

Scott Wolter, PG
President
MN License #30024

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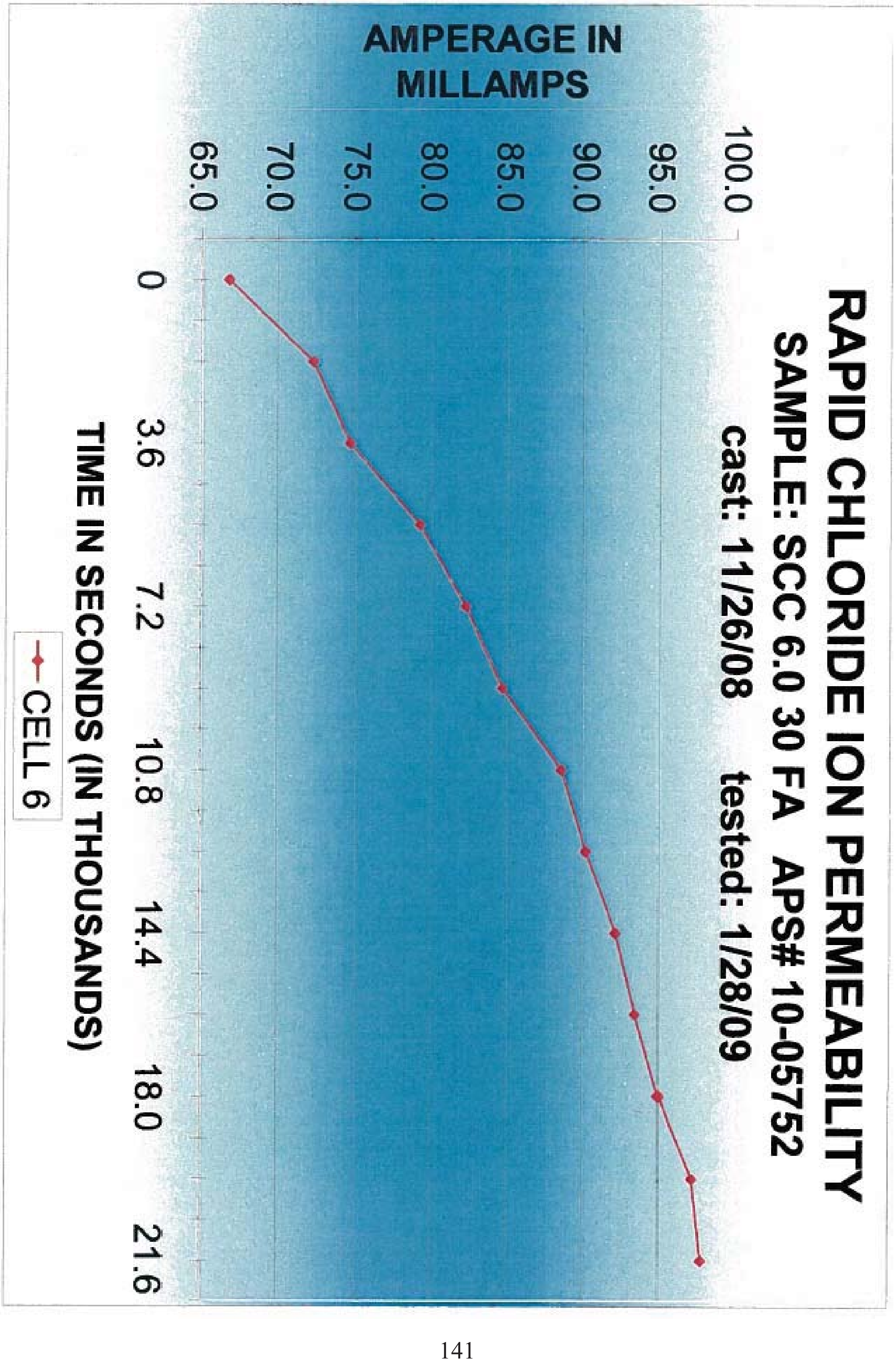

RAPID CHLORIDE ION PERMEABILITY
SAMPLE: SCC 6.0 30 FA APS# 10-05752
cast: 11/26/08 tested: 1/28/09
AMPERAGE IN MILLAMPS
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 6

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
UPSON II ROOM 260
243 CENTENNIAL DRIVE STOP 8115
GRAND FORKS, ND 58202-8115
ATTN: JOE TONNESON

APS JOB NO: 10-05752

DATE: JANUARY 29, 2009

Sample No:	SCC 6.5 0 FA
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 52 mm (2-1/16") long
Date Cast:	November 21, 2008
Date Tested:	January 28, 2009
Age:	68 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	2450	149.5
Average	2450	149.5

CONFORMANCE: The concrete's chloride permeability is rated as moderate based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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Petrographer

Scott Wolter, PG
President
MN License #30024

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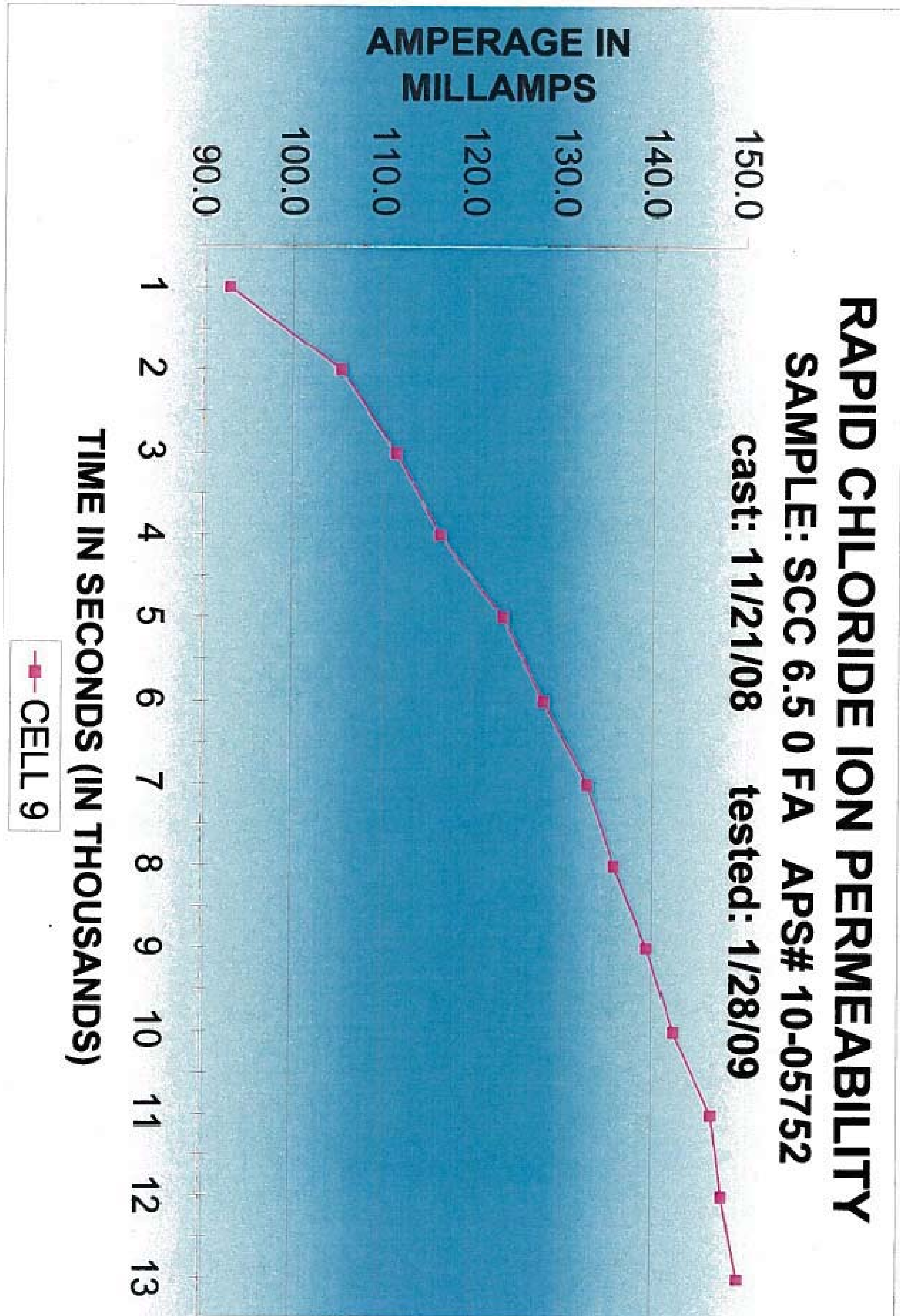
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: SCC 6.5 0 FA APS# 10-05752
cast: 11/21/08 tested: 1/28/09
AMPERAGE IN MILLAMPS
150.0
140.0
130.0
120.0
110.0
100.0
90.0
1
2
3
4
5
6
7
8
9
10
11
12
13
TIME IN SECONDS (IN THOUSANDS)
CELL 9

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF
CONSOLIDATING CONCRETE
FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
UPSON II ROOM 260
243 CENTENNIAL DRIVE STOP 8115
GRAND FORKS, ND 58202-8115
ATTN: JOE TONNESON

APS JOB NO: 10-05752

DATE: JANUARY 29, 2009

Sample No:	SCC 6.5 30 FA
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 54 mm (2-1/8") long
Date Cast:	November 22, 2008
Date Tested:	January 28, 2009
Age:	67 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1340	79.8
Average	1340	79.8

CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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Scott Wolter, PG
President
MN License #30024

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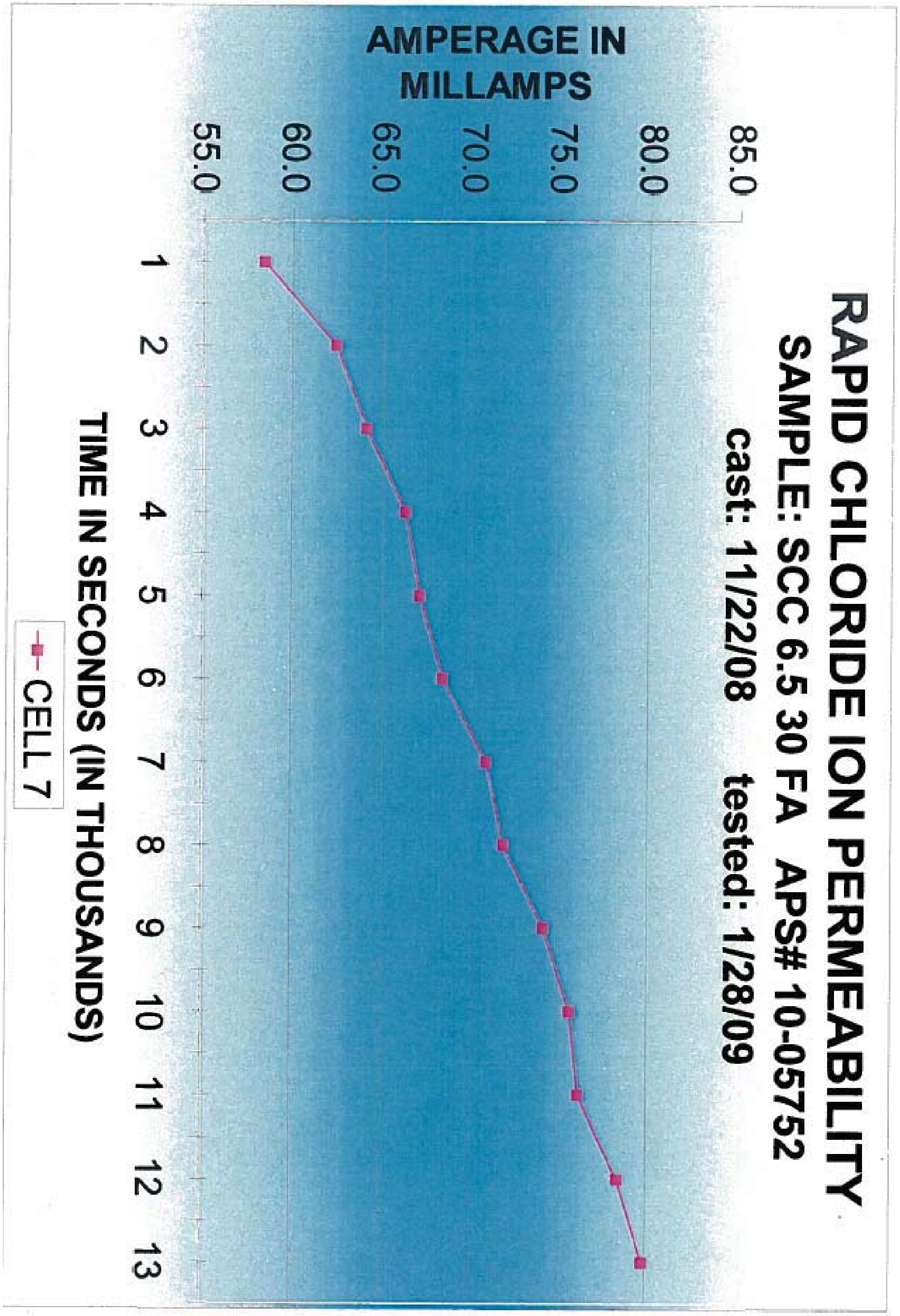

RAPID CHLORIDE ION PERMEABILITY
SAMPLE: SCC 6.5 30 FA APS# 10-05752
cast: 11/22/08 tested: 1/28/09
AMPERAGE IN MILLAMPS
85.0
80.0
75.0
70.0
65.0
60.0
55.0
1
2
3
4
5
6
7
8
9
10
11
12
13
TIME IN SECONDS (IN THOUSANDS)
CELL 7

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
UPSON II ROOM 260
243 CENTENNIAL DRIVE STOP 8115
GRAND FORKS, ND 58202-8115
ATTN: JOE TONNESON

APS JOB NO: 10-05752

DATE: JANUARY 29, 2009

Sample No:	NC 6.0 30 FA
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 52 mm (2-1/16") long
Date Cast:	November 26, 2008
Date Tested:	January 28, 2009
Age:	63 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1240	73.5
Average	1240	73.5

CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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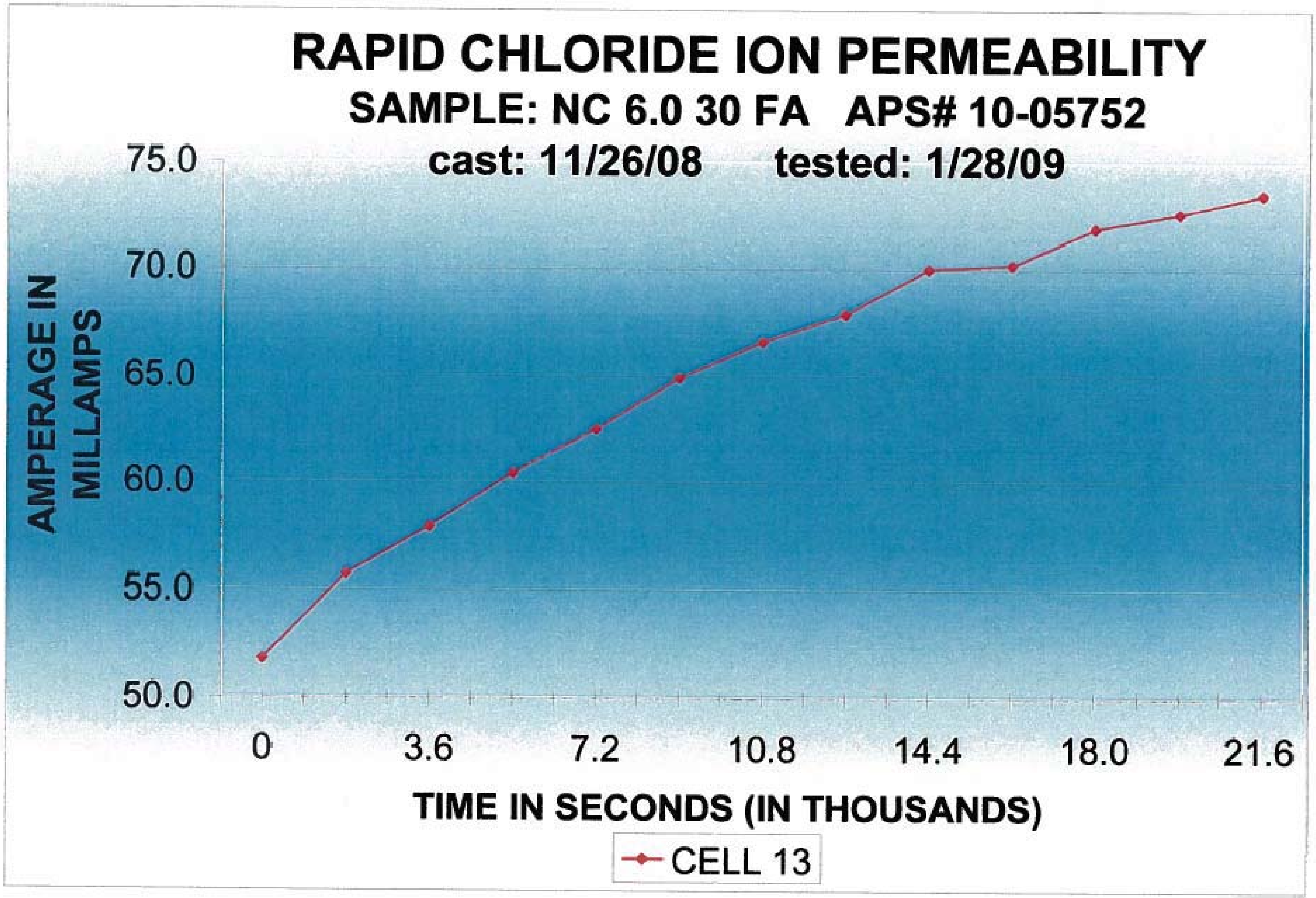
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: NC 6.0 30 FA APS# 10-05752
cast: 11/26/08 tested: 1/28/09
AMPERAGE IN MILLAMPS
75.0
70.0
65.0
60.0
55.0
50.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 13

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
UPSON II ROOM 260
243 CENTENNIAL DRIVE STOP 8115
GRAND FORKS, ND 58202-8115
ATTN: JOE TONNESON

APS JOB NO: 10-05752

DATE: JANUARY 29, 2009

Sample No:	NC 6.5 0 FA
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 52 mm (2-1/16") long
Date Cast:	November 21, 2008
Date Tested:	January 28, 2009
Age:	68 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	2170	133.7
Average	2170	133.7

CONFORMANCE: The concrete's chloride permeability is rated as moderate based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

Megan Koch
Petrographer

Scott Wolter, PG
President
MN License #30024

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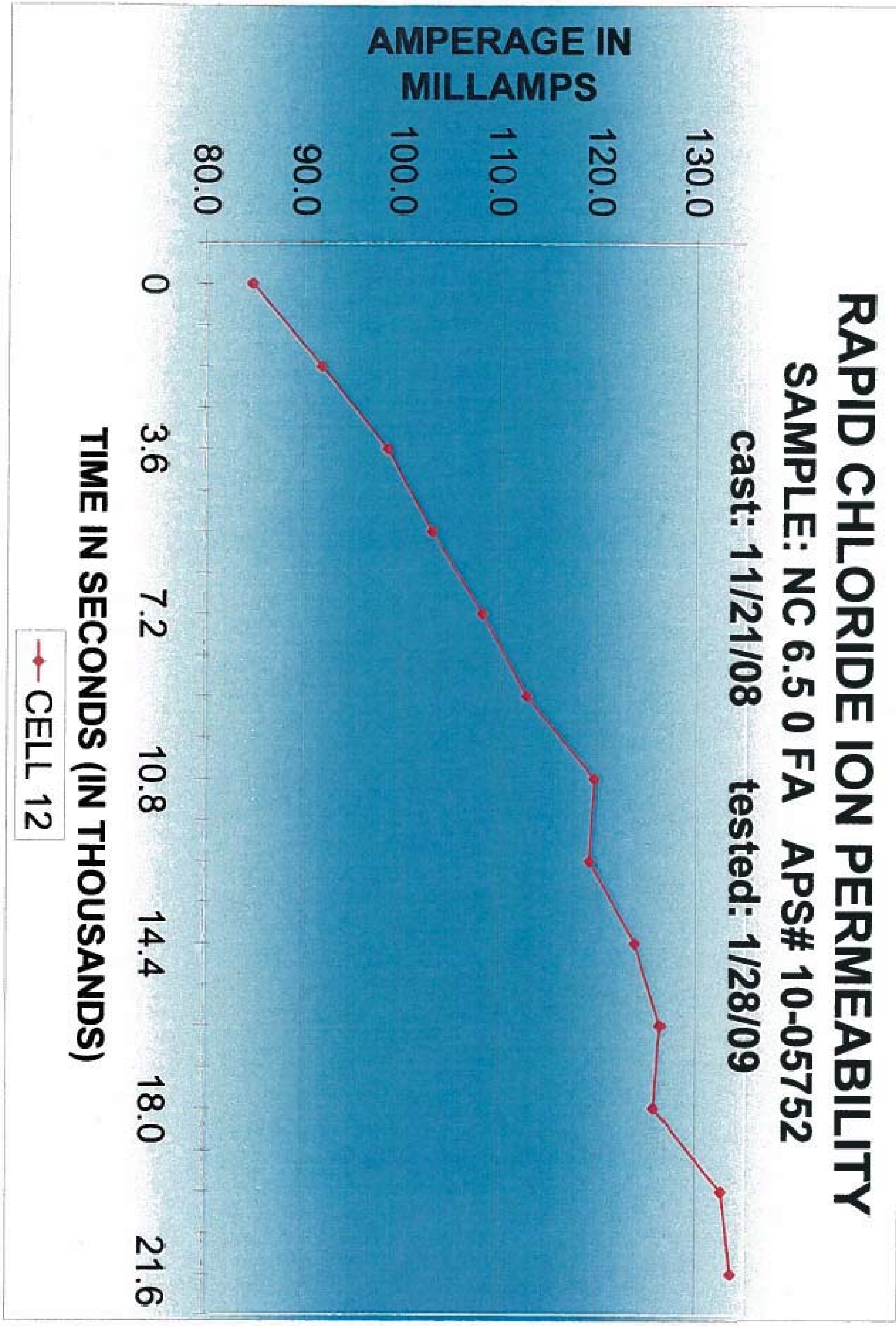
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: NC 6.5 0 FA APS# 10-05752
cast: 11/21/08 tested: 1/28/09
AMPERAGE IN MILLAMPS
130.0
120.0
110.0
100.0
90.0
80.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 12

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
UPSON II ROOM 260
243 CENTENNIAL DRIVE STOP 8115
GRAND FORKS, ND 58202-8115
ATTN: JOE TONNESON

APS JOB NO: 10-05752

DATE: JANUARY 29, 2009

Sample No:	NC 6.5 30 FA
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 51 mm (2") long
Date Cast:	November 22, 2008
Date Tested:	January 28, 2009
Age:	67 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1120	65.8
Average	1120	65.8

CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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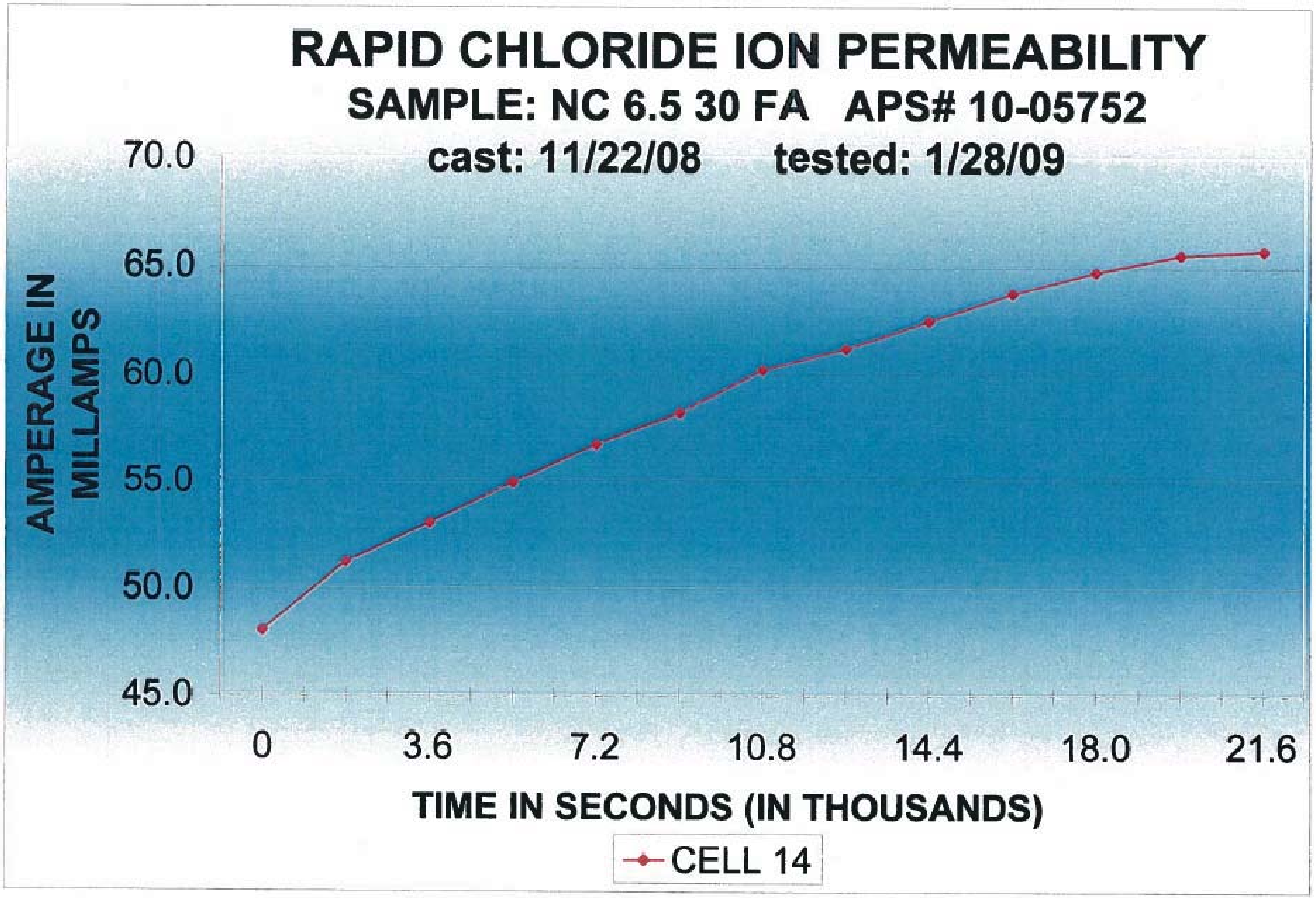
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: NC 6.5 30 FA APS# 10-05752
cast: 11/22/08 tested: 1/28/09
AMPERAGE IN MILLAMPS
70.0
65.0
60.0
55.0
50.0
45.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 14

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID CI⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
243 CENTENNIAL DRIVE STOP 8155
UPSON II ROOM 260
GRAND FORKS, ND 58202-8155

ATTN: JOE TONNESON

APS JOB NO: 10-05777

DATE: FEBRUARY 20, 2009

Sample No:	SCC:6.5:0FA T9 Bot
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 51 mm (2") long
Date Cast:	November 20, 2008
Date Tested:	February 18, 2009
Age:	90 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	2270	136.6
Average	2270	136.6

CONFORMANCE: The concrete's chloride permeability is rated as moderate based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

Megan Koch
Petrographer

Scott Wolter, PG
President
MN License #30024

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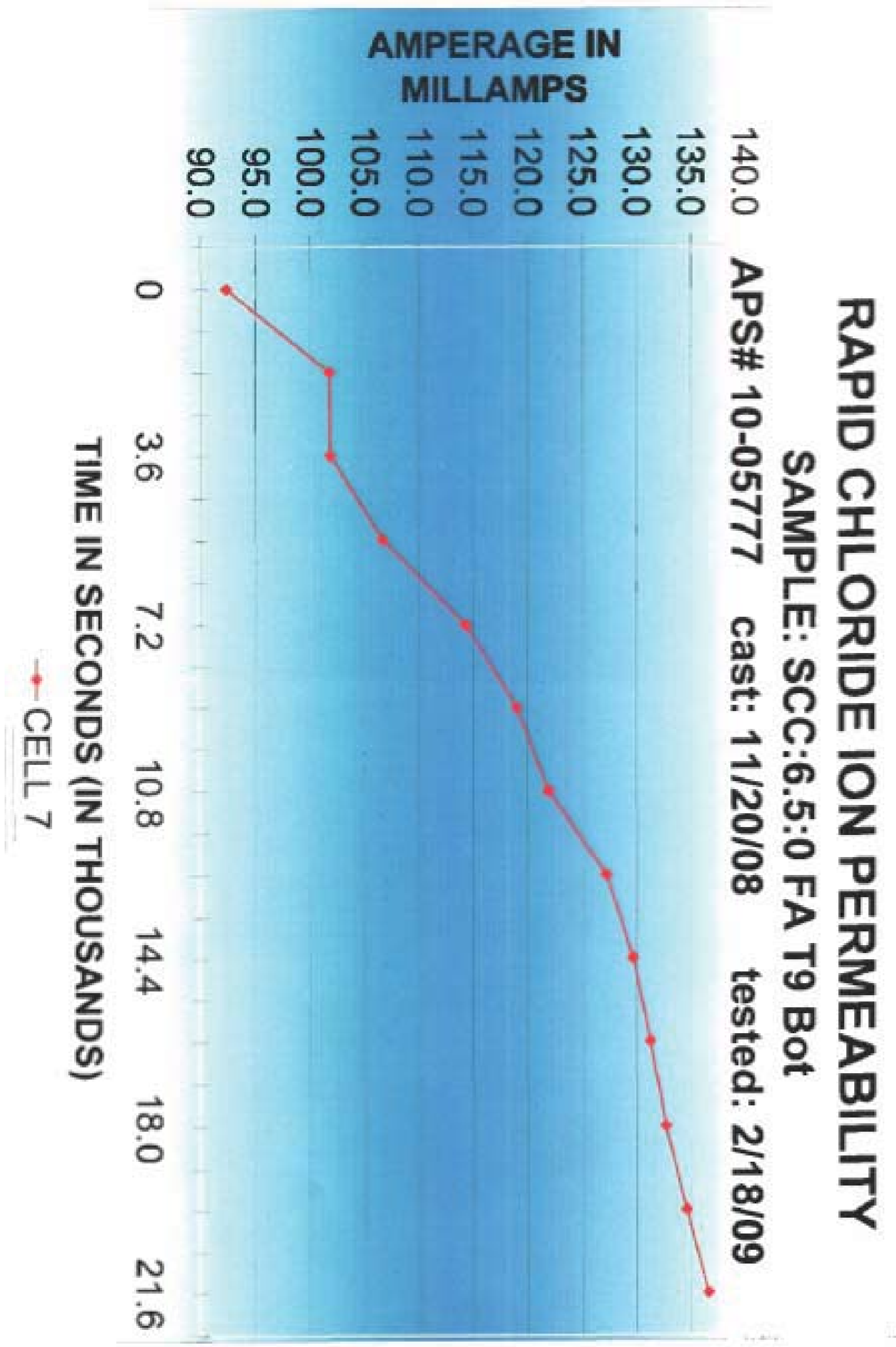


RAPID CHLORIDE ION PERMEABILITY
SAMPLE: SCC:6.5:0 FA T9 Bot
APS# 10-05777 cast: 11/20/08 tested: 2/18/09
AMPERAGE IN MILLAMPS
140.0
135.0
130.0
125.0
120.0
115.0
110.0
105.0
100.0
95.0
90.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 7

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
243 CENTENNIAL DRIVE STOP 8155
UPSON II ROOM 260
GRAND FORKS, ND 58202-8155

ATTN: JOE TONNESON

APS JOB NO: 10-05777

DATE: FEBRUARY 20, 2009

Sample No:	SCC:6.5:0FA Trial 13 Mid
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	103 mm (4-1/16") diameter x 51 mm (2") long
Date Cast:	November 20, 2008
Date Tested:	February 18, 2009
Age:	90 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1910	120.7
Average	1910	120.7

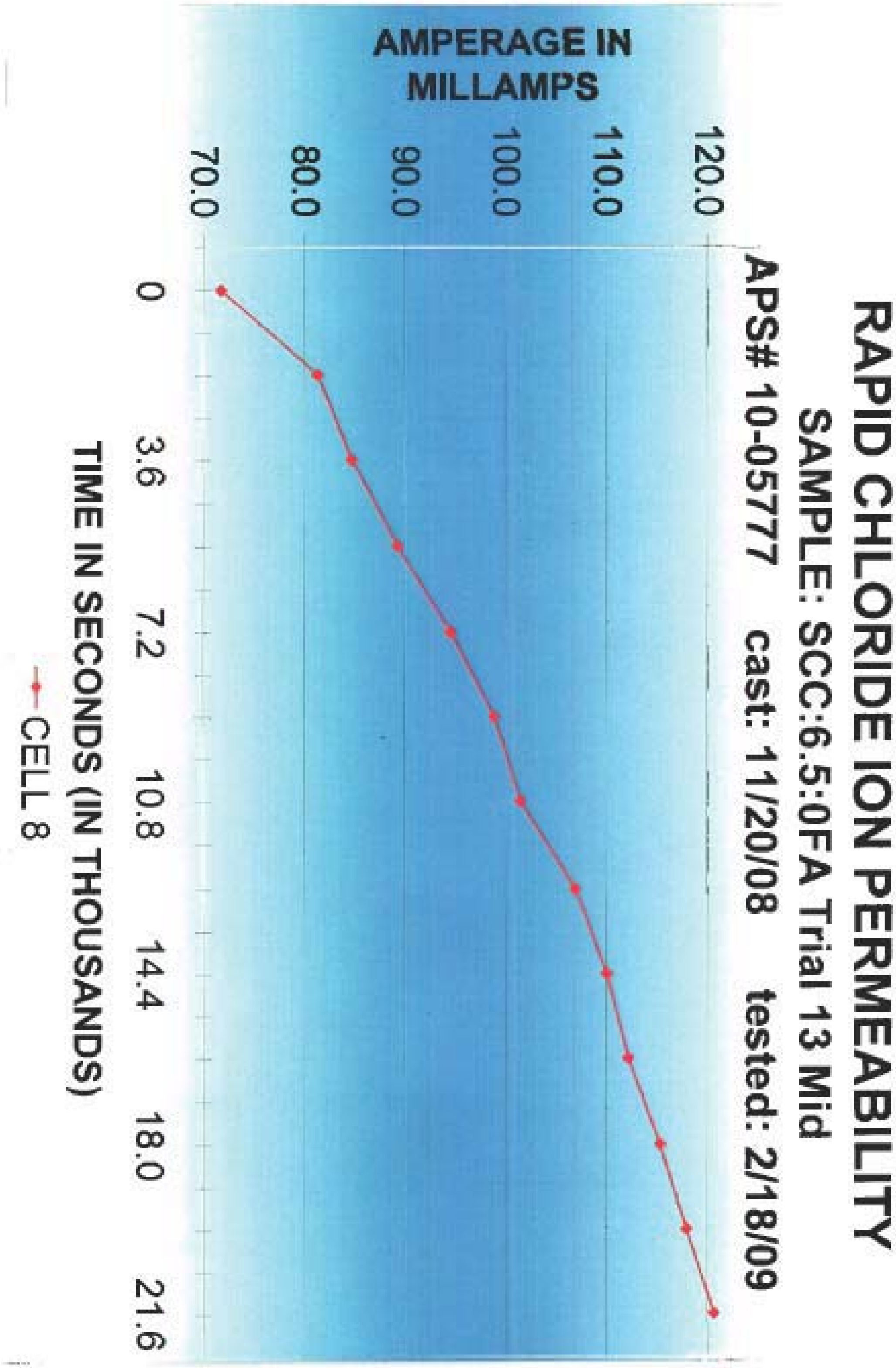
CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

Megan Koch
Petrographer

Scott Wolter, PG
President
MN License #30024



RAPID CHLORIDE ION PERMEABILITY
SAMPLE: SCC:6.5:0FA Trial 13 Mid
APS# 10-05777 cast: 11/20/08 tested: 2/18/09
AMPERAGE IN MILLAMPS
120.0
110.0
100.0
90.0
80.0
70.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 8

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID CL PERMEABILITY TESTING

PROJECT:	REPORTED TO:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT	UNIVERSITY OF NORTH DAKOTA DEPARTMENT OF CIVIL ENGINEERING 243 CENTENNIAL DRIVE STOP 8155 UPSON II ROOM 260 GRAND FORKS, ND 58202-8155
	ATTN: JOE TONNESON
APS JOB NO: 10-05777	**DATE:** FEBRUARY 20, 2009

Sample No:	SCC:6.5:30FA 726
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	103 mm (4-1/16") diameter x 49 mm (1-15/16") long
Date Cast:	November 20, 2008
Date Tested:	February 18, 2009
Age:	90 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	2580	163.0
Average	2580	163.0

CONFORMANCE: The concrete's chloride permeability is rated as moderate based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

Megan Koch Petrographer	Scott Wolter, PG President

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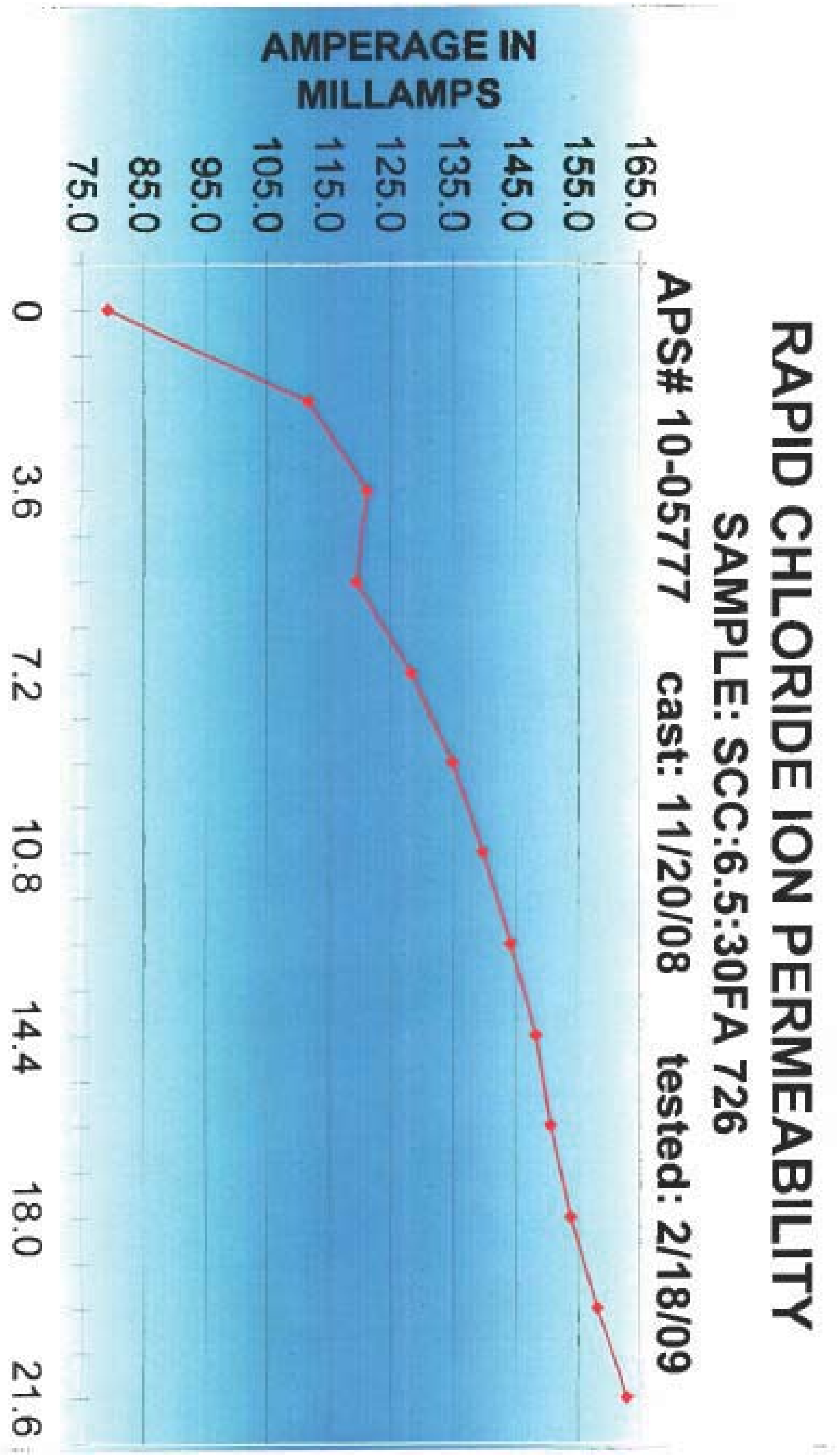
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: SCC:6.5:30FA 726
APS# 10-05777 cast: 11/20/08 tested: 2/18/09
AMPERAGE IN MILLAMPS
165.0
155.0
145.0
135.0
125.0
115.0
105.0
95.0
85.0
75.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 9

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT: EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT	**REPORTED TO:** UNIVERSITY OF NORTH DAKOTA DEPARTMENT OF CIVIL ENGINEERING 243 CENTENNIAL DRIVE STOP 8155 UPSON II ROOM 260 GRAND FORKS, ND 58202-8155
	ATTN: JOE TONNESON
APS JOB NO: 10-05777	**DATE:** FEBRUARY 20, 2009

Sample No:	SCC:6.0:30FA Top
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 51 mm (2") long
Date Cast:	November 25, 2008
Date Tested:	February 19, 2009
Age:	86 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1450	88.5
Average	1450	88.5

CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

Megan Koch
Petrographer

Scott Wolter, PG
President
MN License #30024

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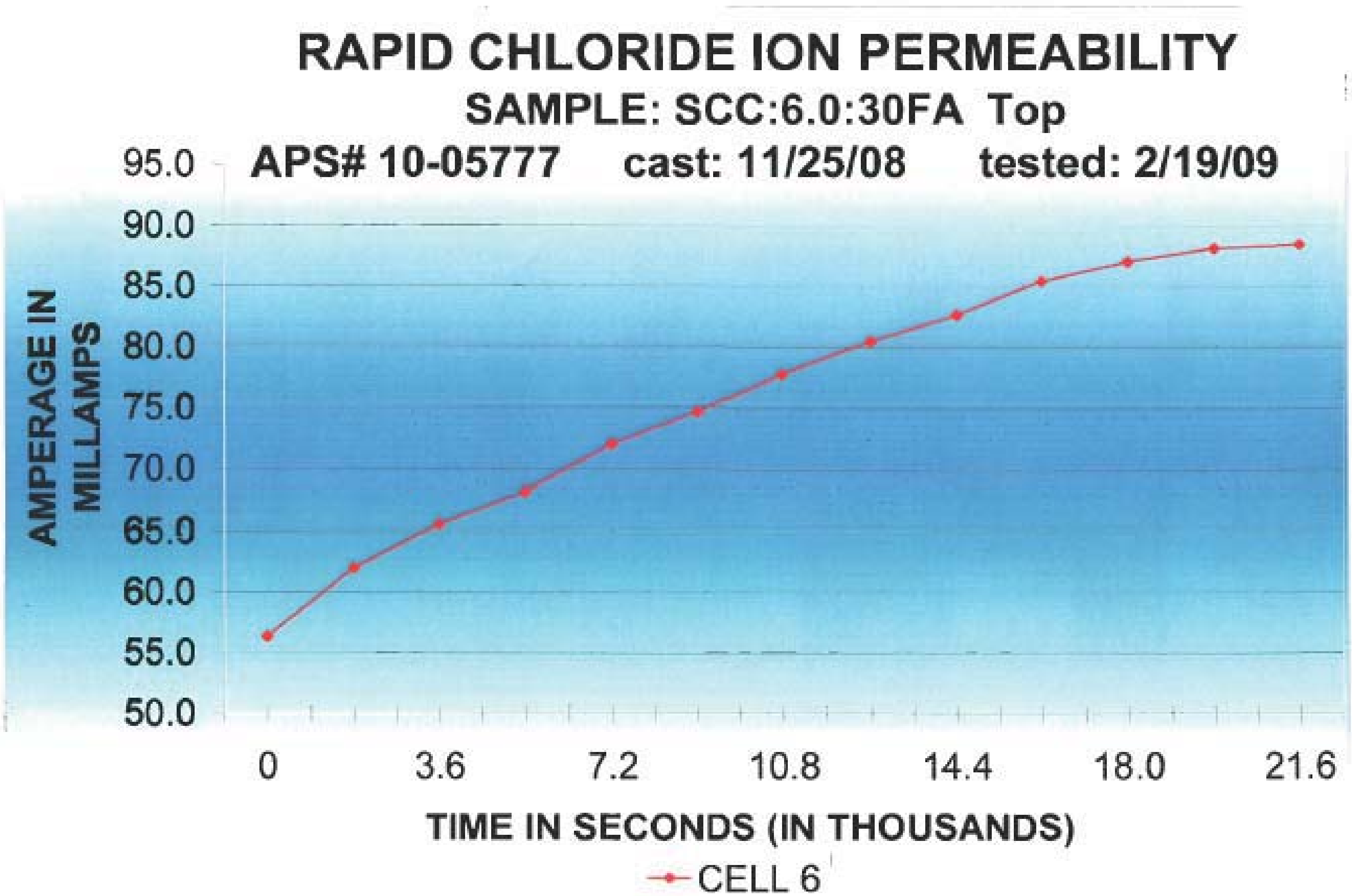
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: SCC:6.0:30FA Top
APS# 10-05777 cast: 11/25/08 tested: 2/19/09
AMPERAGE IN MILLAMPS
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 6

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
243 CENTENNIAL DRIVE STOP 8155
UPSON II ROOM 260
GRAND FORKS, ND 58202-8155

ATTN: JOE TONNESON

APS JOB NO: 10-05777

DATE: FEBRUARY 20, 2009

Sample No:	SCC:6.5:30FA T19
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 51 mm (2") long
Date Cast:	November 20, 2008
Date Tested:	February 19, 2009
Age:	91 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1050	63.2
Average	1050	63.2

CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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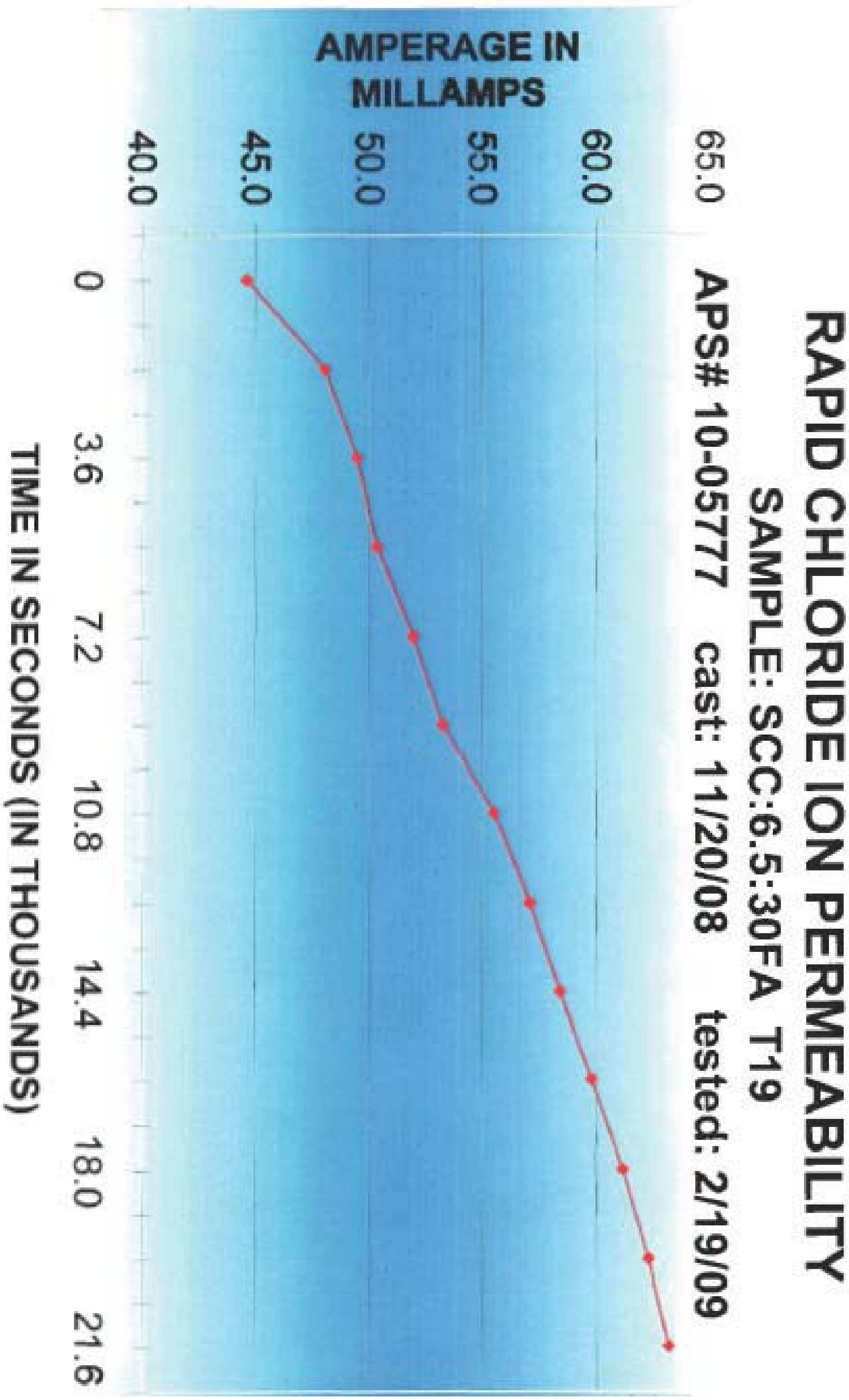

RAPID CHLORIDE ION PERMEABILITY
SAMPLE: SCC:6.5:30FA T19
APS# 10-05777 cast: 11/20/08 tested: 2/19/09
AMPERAGE IN MILLAMPS
65.0
60.0
55.0
50.0
45.0
40.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 7

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
243 CENTENNIAL DRIVE STOP 8155
UPSON II ROOM 260
GRAND FORKS, ND 58202-8155

ATTN: JOE TONNESON

APS JOB NO: 10-05777

DATE: FEBRUARY 20, 2009

Sample No:	SCC:6.0:30FA Bot
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 51 mm (2") long
Date Cast:	November 25, 2008
Date Tested:	February 19, 2009
Age:	86 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1180	73.0
Average	1180	73.0

CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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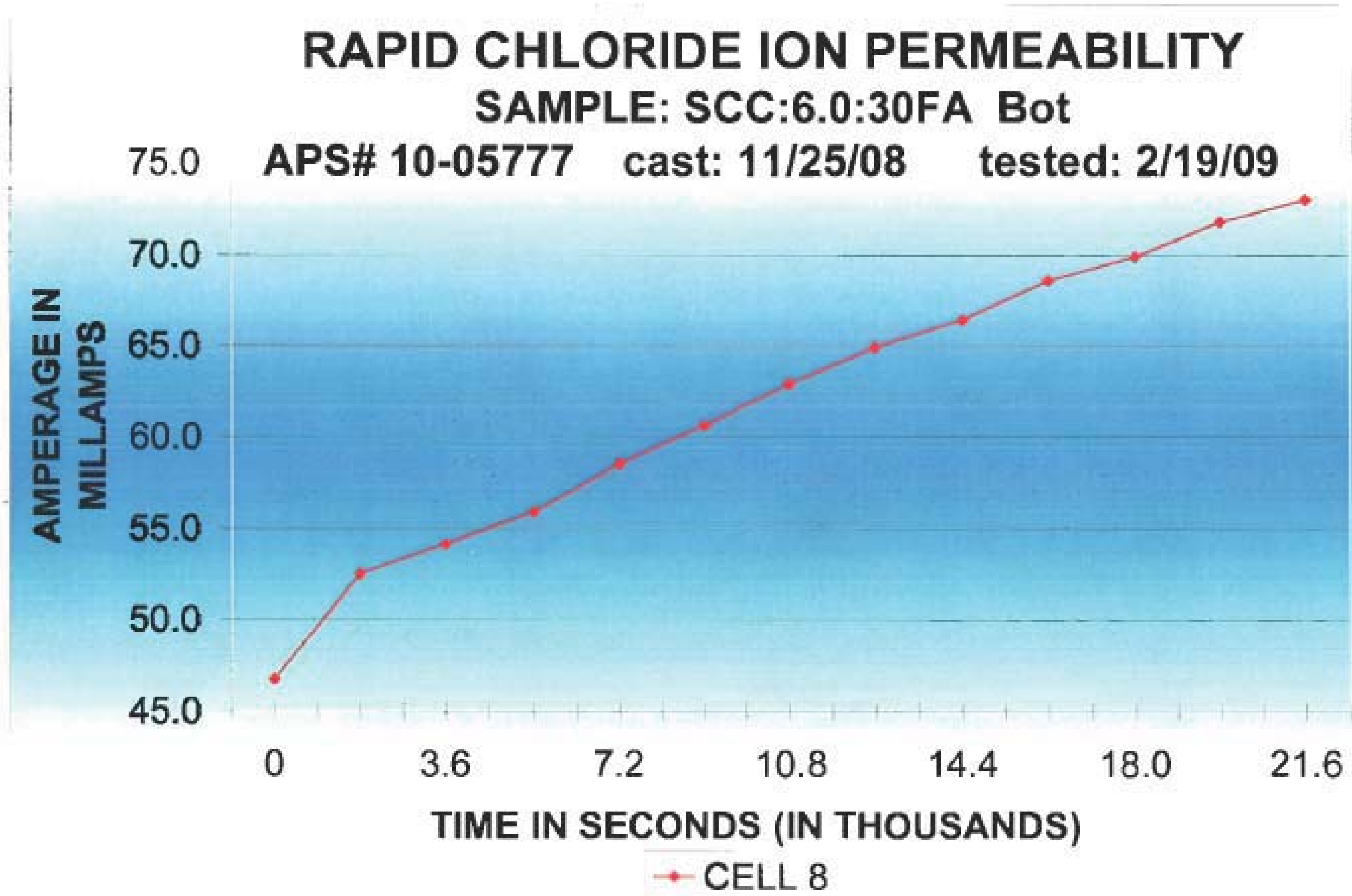
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: SCC:6.0:30FA Bot
APS# 10-05777 cast: 11/25/08 tested: 2/19/09
AMPERAGE IN MILLAMPS
75.0
70.0
65.0
60.0
55.0
50.0
45.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 8

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
243 CENTENNIAL DRIVE STOP 8155
UPSON II ROOM 260
GRAND FORKS, ND 58202-8155

ATTN: JOE TONNESON

APS JOB NO: 10-05777

DATE: FEBRUARY 20, 2009

Sample No:	NC:6.5:30FA T17 Top
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 51 mm (2") long
Date Cast:	November 20, 2008
Date Tested:	February 19, 2009
Age:	91 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	900	52.9
Average	900	52.9

CONFORMANCE: The concrete's chloride permeability is rated as very low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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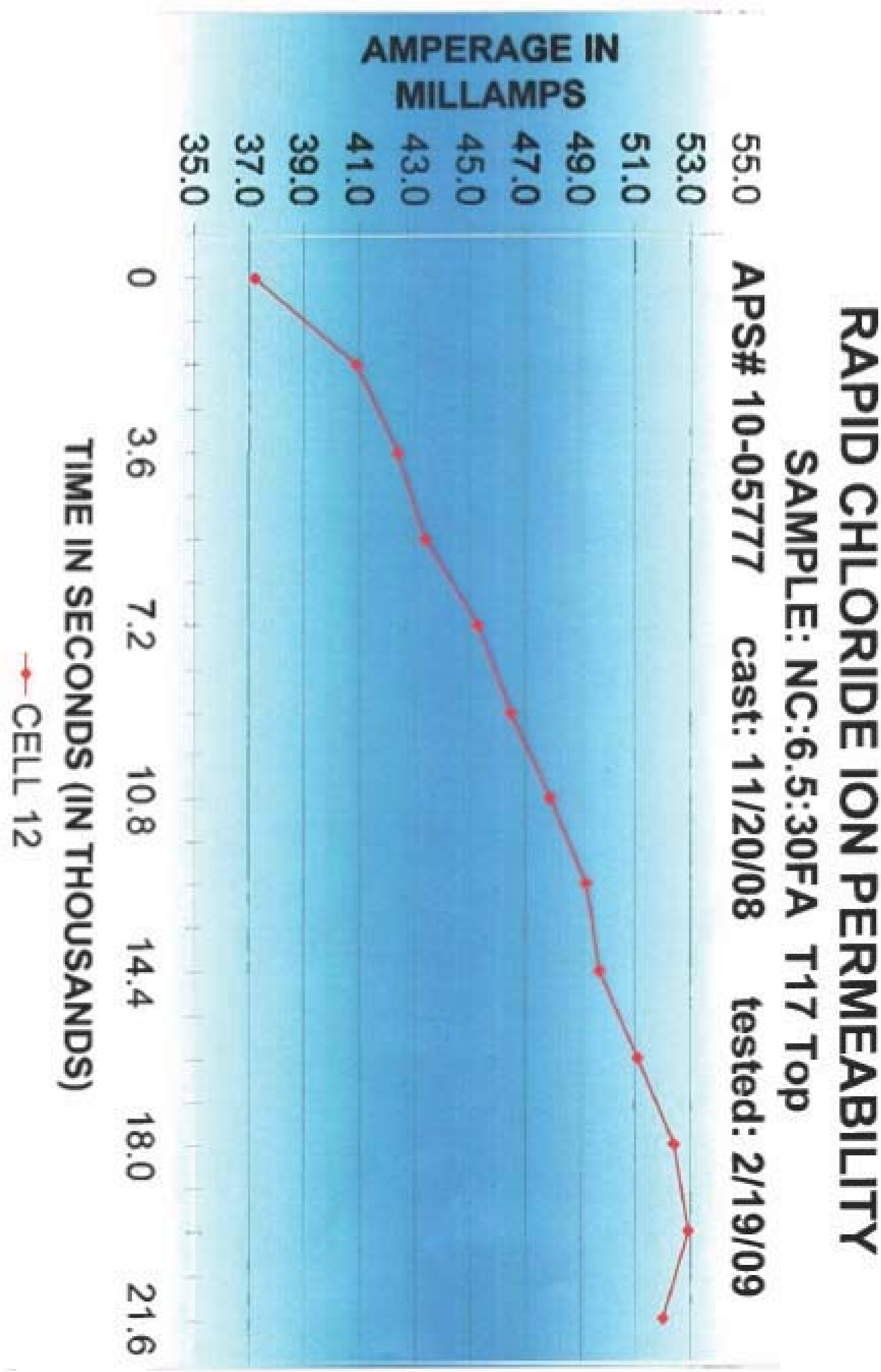

RAPID CHLORIDE ION PERMEABILITY
SAMPLE: NC:6.5:30FA T17 Top
APS# 10-05777 cast: 11/20/08 tested: 2/19/09
AMPERAGE IN MILLAMPS
55.0
53.0
51.0
49.0
47.0
45.0
43.0
41.0
39.0
37.0
35.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 12

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:	**REPORTED TO:**
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT	UNIVERSITY OF NORTH DAKOTA DEPARTMENT OF CIVIL ENGINEERING 243 CENTENNIAL DRIVE STOP 8155 UPSON II ROOM 260 GRAND FORKS, ND 58202-8155
	ATTN: JOE TONNESON
APS JOB NO: 10-05777	**DATE:** FEBRUARY 20, 2009

Sample No:	NC:6.0:30FA Sample I
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 52 mm (2-1/16") long
Date Cast:	November 25, 2008
Date Tested:	February 19, 2009
Age:	86 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1130	69.6
Average	1130	69.6

CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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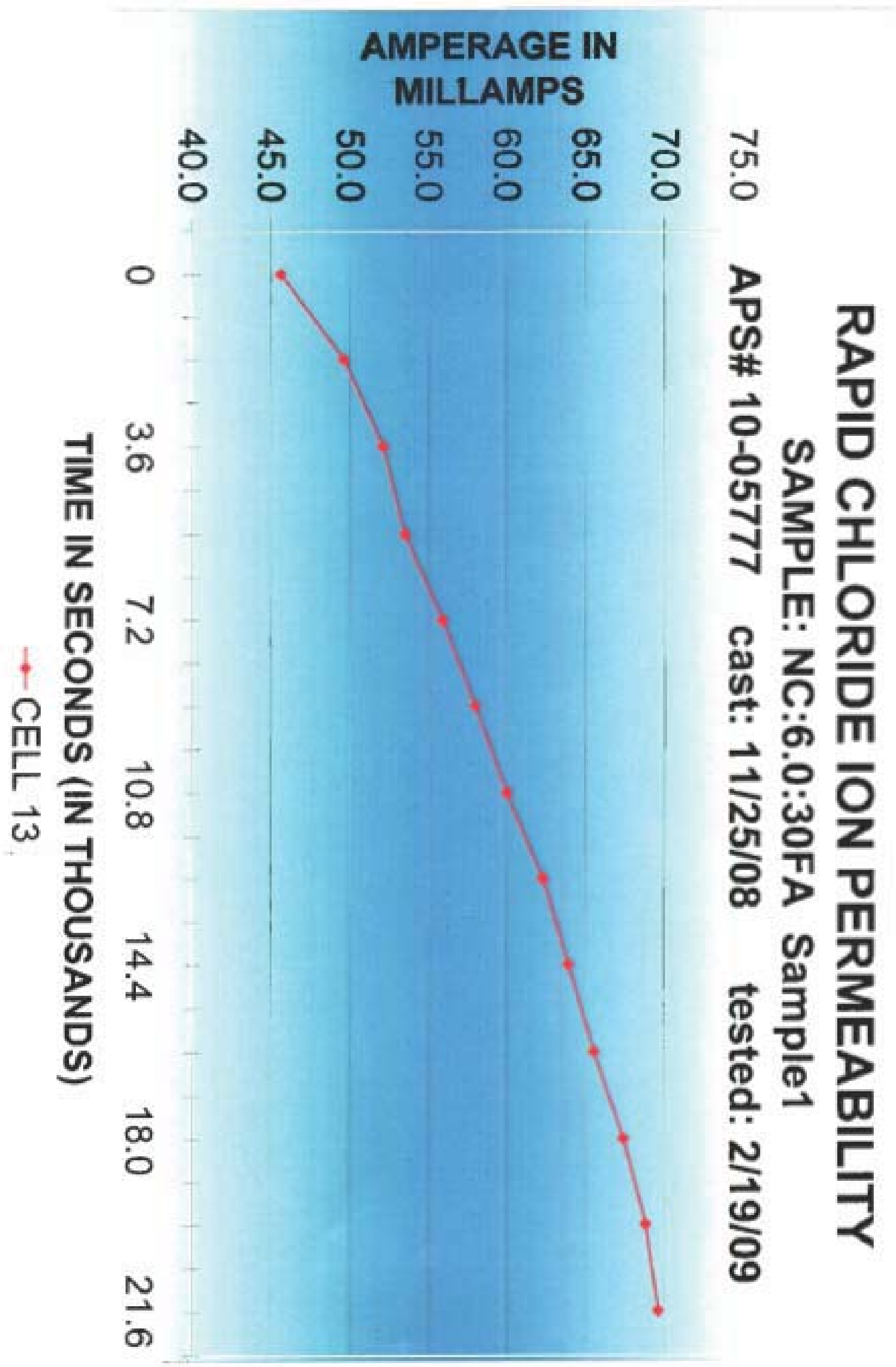
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: NC:6.0:30FA Sample1
APS# 10-05777 cast: 11/25/08 tested: 2/19/09
AMPERAGE IN MILLAMPS
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 13

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT: EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT	**REPORTED TO:** UNIVERSITY OF NORTH DAKOTA DEPARTMENT OF CIVIL ENGINEERING 243 CENTENNIAL DRIVE STOP 8155 UPSON II ROOM 260 GRAND FORKS, ND 58202-8155
	ATTN: JOE TONNESON
APS JOB NO: 10-05777	**DATE:** FEBRUARY 20, 2009

Sample No:	NC:6.5:30FA T17
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 51 mm (2") long
Date Cast:	November 20, 2008
Date Tested:	February 19, 2009
Age:	91 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	670	39.7
Average	670	39.7

CONFORMANCE: The concrete's chloride permeability is rated as very low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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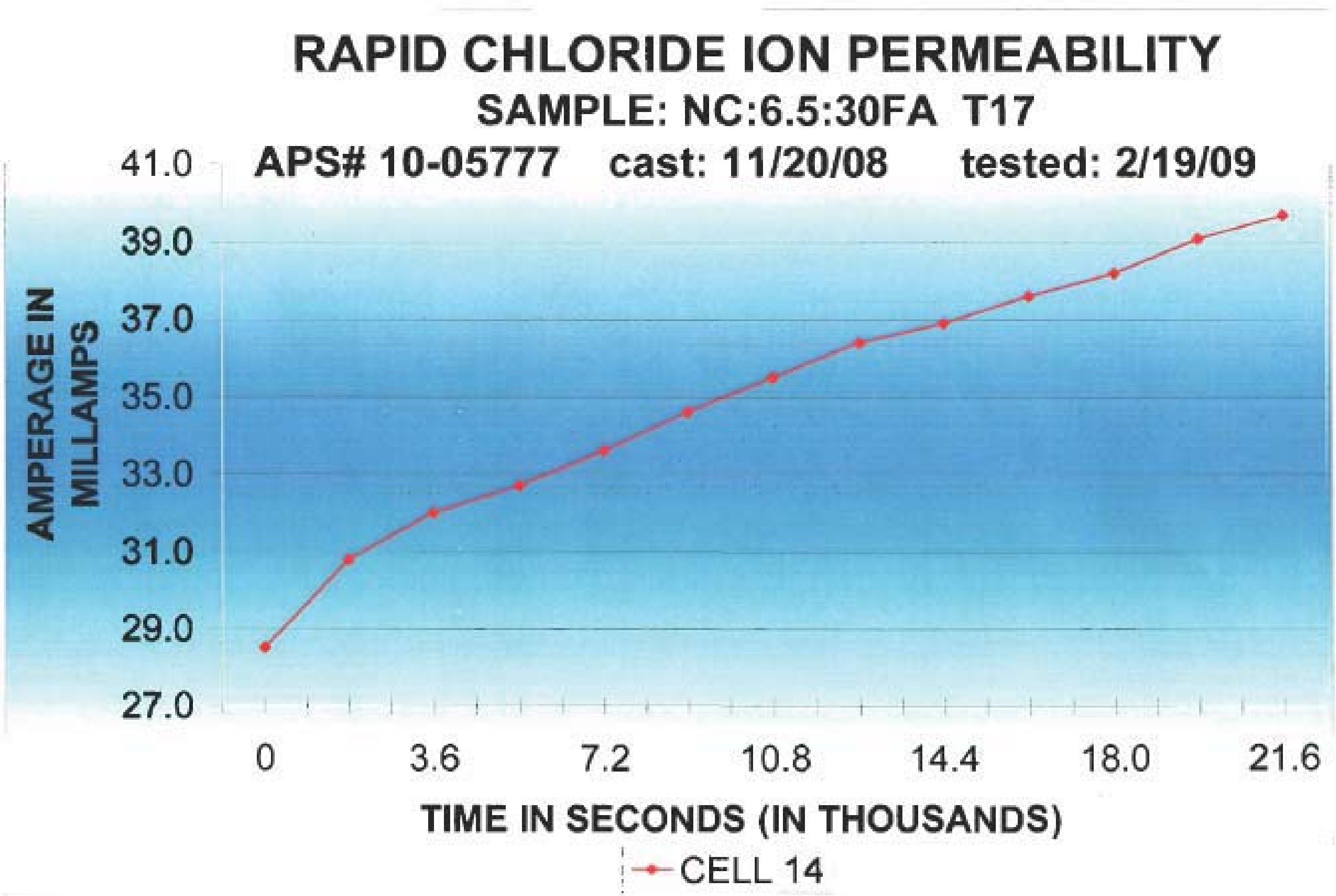

RAPID CHLORIDE ION PERMEABILITY
SAMPLE: NC:6.5:30FA T17
APS# 10-05777 cast: 11/20/08 tested: 2/19/09
AMPERAGE IN MILLAMPS
41.0
39.0
37.0
35.0
33.0
31.0
29.0
27.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 14

AMERICAN
PETROGRAPHIC
SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF
CONSOLIDATING CONCRETE
FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
243 CENTENNIAL DRIVE STOP 8155
UPSON II ROOM 260
GRAND FORKS, ND 58202-8155

ATTN: JOE TONNESON

APS JOB NO: 10-05777

DATE: FEBRUARY 20, 2009

Sample No:	NC:6.5:0.0FA
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 52 mm (2-1/16") long
Date Cast:	November 20, 2008
Date Tested:	February 19, 2009
Age:	91 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	1750	111.6
Average	1750	111.6

CONFORMANCE: The concrete's chloride permeability is rated as low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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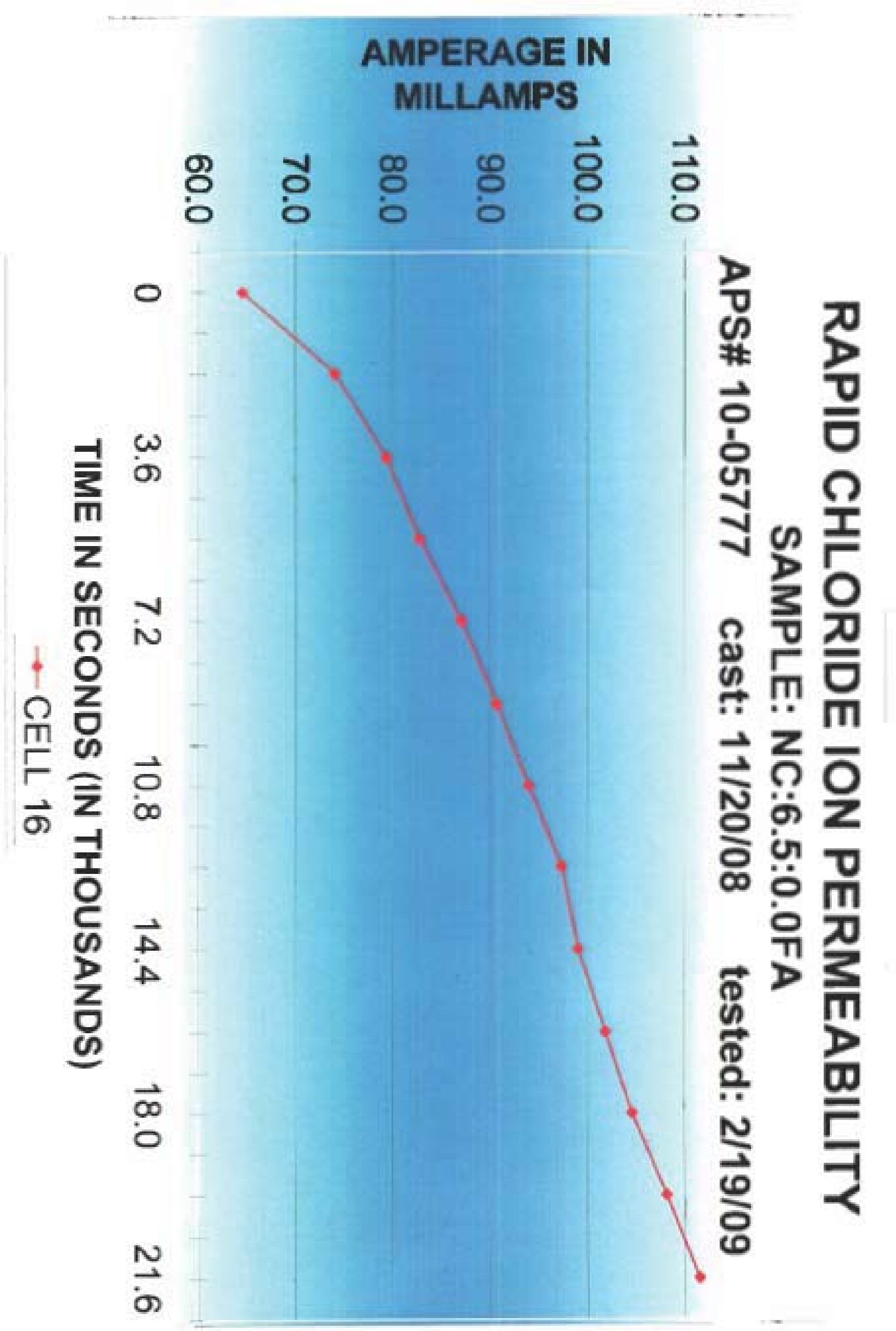

RAPID CHLORIDE ION PERMEABILITY
SAMPLE: NC:6.5:0.0FA
APS# 10-05777 cast: 11/20/08 tested: 2/19/09
AMPERAGE IN MILLAMPS
110.0
100.0
90.0
80.0
70.0
60.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 16

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl^{-} PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF CONSOLIDATING CONCRETE FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
243 CENTENNIAL DRIVE STOP 8155
UPSON II ROOM 260
GRAND FORKS, ND 58202-8155

ATTN: JOE TONNESON

APS JOB NO: 10-05777

DATE: FEBRUARY 20, 2009

Sample No:	NC:6.5:NOFA
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 52 mm (2-1/16") long
Date Cast:	November 20, 2008
Date Tested:	February 19, 2009
Age:	91 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	2490	162.0
Average	2490	162.0

CONFORMANCE: The concrete's chloride permeability is rated as moderate based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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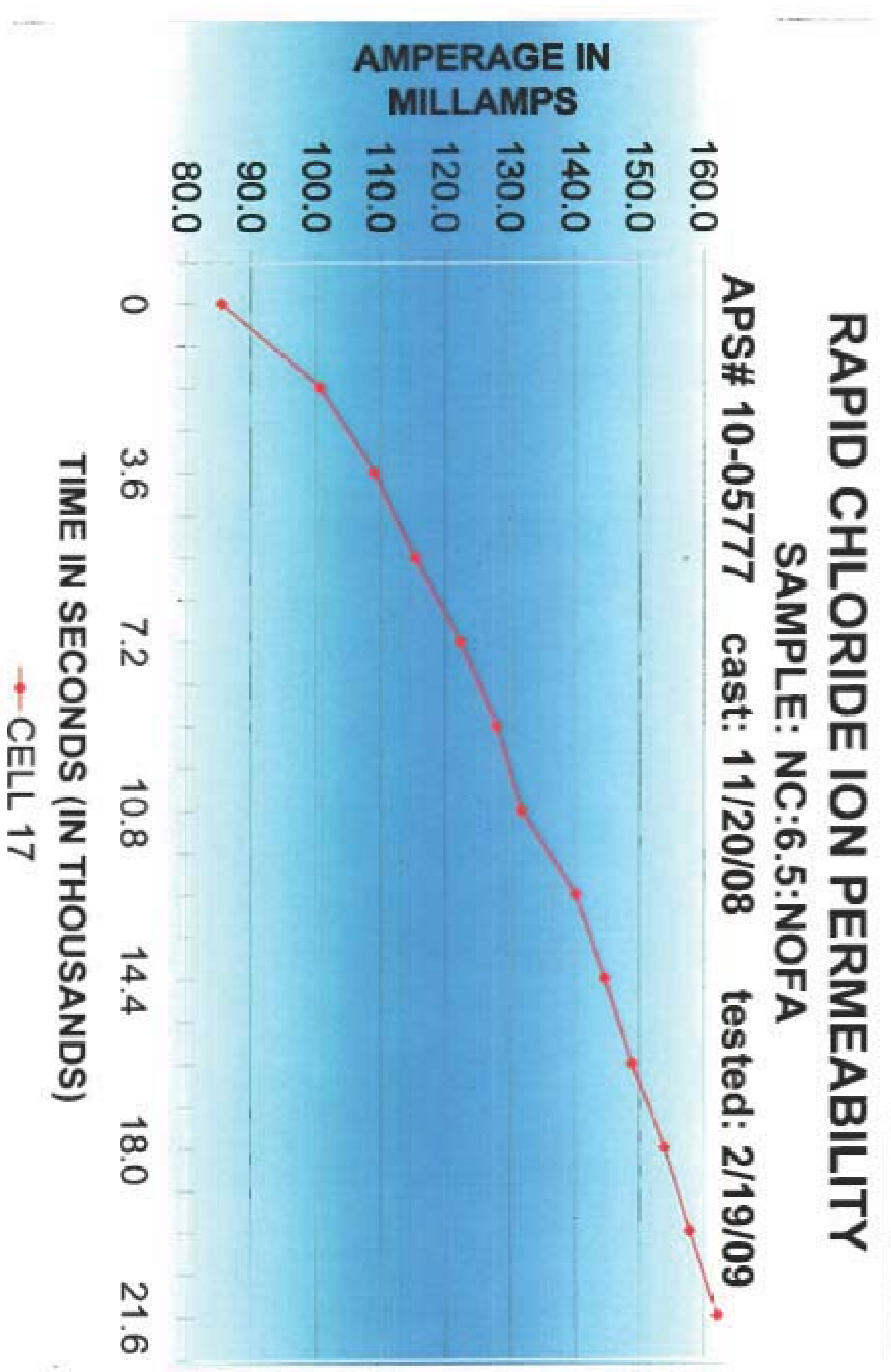
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: NC:6.5:NOFA
APS# 10-05777 cast: 11/20/08 tested: 2/19/09
AMPERAGE IN MILLAMPS
160.0
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 17

AMERICAN PETROGRAPHIC SERVICES, INC.

REPORT OF RAPID Cl⁻ PERMEABILITY TESTING

PROJECT:
EVALUATION OF SELF
CONSOLIDATING CONCRETE
FOR NDDOT

REPORTED TO:
UNIVERSITY OF NORTH DAKOTA
DEPARTMENT OF CIVIL ENGINEERING
243 CENTENNIAL DRIVE STOP 8155
UPSON II ROOM 260
GRAND FORKS, ND 58202-8155

ATTN: JOE TONNESON

APS JOB NO: 10-05777

DATE: FEBRUARY 20, 2009

Sample No:	NC:6.0:30FA Sample 2
Sample Submitted by:	Joe Tonneson
Sample Description:	Section of Hardened Concrete Cylinder
Sample Dimensions:	101 mm (4") diameter x 52 mm (2-1/16") long
Date Cast:	November 25, 2008
Date Tested:	February 19, 2009
Age:	86 Days

TEST RESULTS:

	Coulombs	Milliamps (Maximum)
Trial 1	890	54.3
Average	890	54.3

CONFORMANCE: The concrete's chloride permeability is rated as very low based on the criteria outlined in AASHTO:T 277 and ASTM:C 1202.

TEST PROCEDURE: Testing was performed in accordance with APS Standard Operating Procedure 00 LAB 006 "Rapid Determination of the Chloride Permeability of Concrete" (AASHTO:T 277 and ASTM:C 1202). One 2-inch long "puck" from a 4-inch diameter cylinder was submitted for analysis.

Remarks: The unused portion of the test sample will be retained for a period of at least thirty days from the date of this report. Unless further instructions are received by that time, the sample may be discarded. The test results relate only to the sample tested. No warranty, express or implied, is made.

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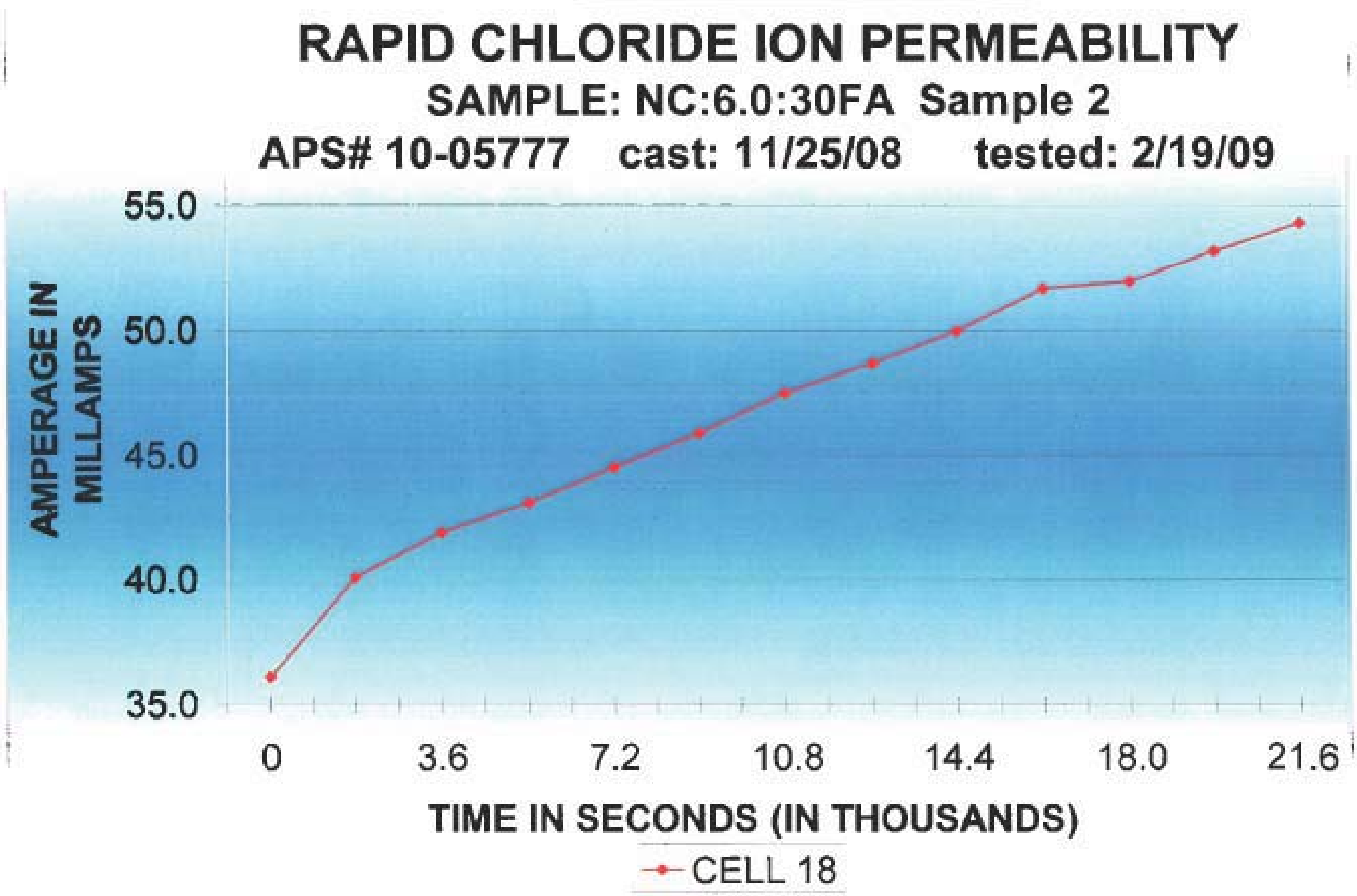
RAPID CHLORIDE ION PERMEABILITY
SAMPLE: NC:6.0:30FA Sample 2
APS# 10-05777 cast: 11/25/08 tested: 2/19/09
AMPERAGE IN MILLAMPS
55.0
50.0
45.0
40.0
35.0
0
3.6
7.2
10.8
14.4
18.0
21.6
TIME IN SECONDS (IN THOUSANDS)
CELL 18

AV: Original Data for Plastic and Hardened State Tests

Table AV.1: Spread flow retention data

	Spread Flow Retention (in) vs. Time Elapsed (min)			
Mix ID	0	15	30	45
SCC:6.5:0.0FA	23	21.5	19	16
SCC:6.5:30FA	26	22	19.5	18
SCC:6.0:30FA	25.75	22	18	17

Table AV.2: Column Segregation, Unit Weight, Air Content, and J-Ring data

Mix ID	Mass retained Top (lbs)	Mass retained, bottom (lbs)	% Static Segregation	Unit Wt (pcf)	Air Content %	J-Ring (in)
SCC:6.5:0.0FA	11	12.35	5.78%	143.064516	5.9	21.5
SCC:6.5:30FA	10.95	12.05	4.78%	144.677419	5.5	25.25
SCC:6.0:30FA	10.7	11.6	4.04%	146.290323	5	25

Table AV.3: Admixture dosage in plastic state data

	Admixtures Dosage (oz./cwt)			
Mix ID	Glenium PS 1466 (HRWRA)	Polyheed 1020 (WR)	Rheomac 450 (VMA)	MB AE 90 (AEA)
SCC:6.5:0.0FA	6	2	0	0.45
SCC:6.5:30FA	5	2	0.4	0.35
SCC:6.0:30FA	6	2	0	0.4

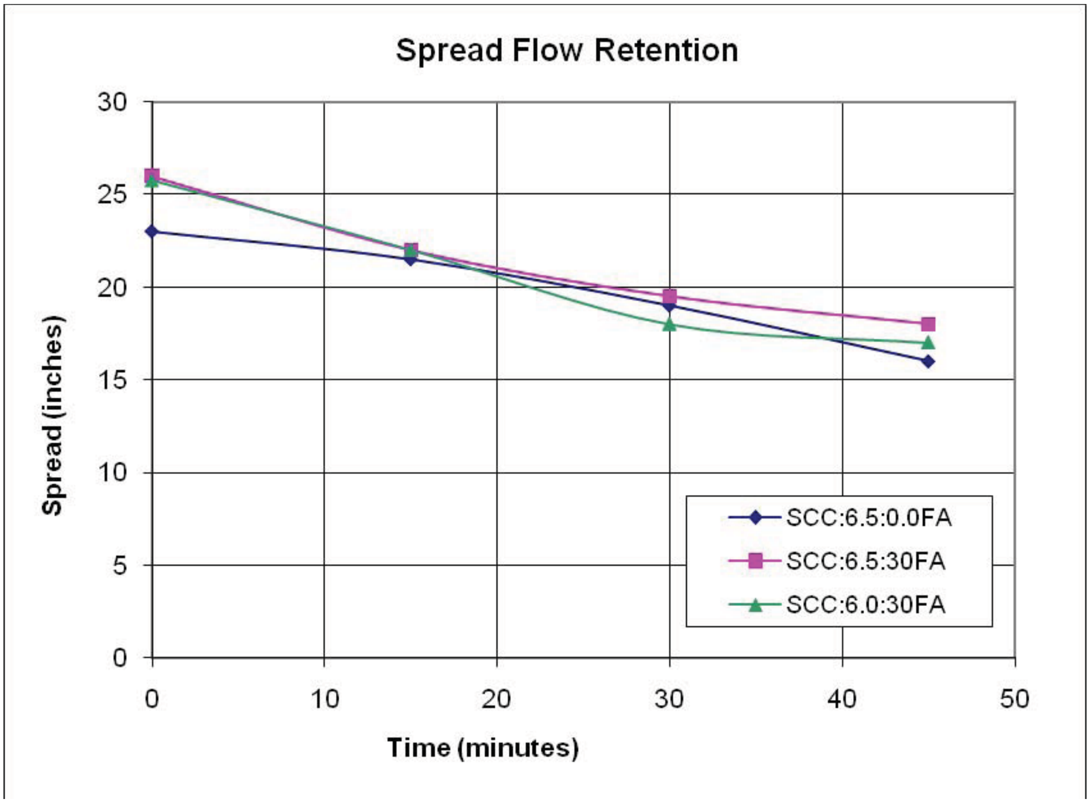

Figure AV.I: Spread flow retention

Table AV.4: Compressive Strength test data

Area	12.57								
Mix ID	Trial #	Unit Weight (pcf)	1 day break strength (psi)	Average	7 day break Strength (psi)	Average	28 day break strength (psi)	Average	7.5√fc'
SCC6.5:30FA	13	146	2345		5408		7574		
SCC6.5:30FA	13	146	2654	2447	5425	5506	7723	7568	652
SCC:6.5:30FA	13	146	2341		5685		7409		
SCC:6.5:0.0FA	5	141	3245		6476		7982		
SCC:6.5:0.0FA	5	141	3163	3246	5985	6276	8110	7858	665
SCC:6.5:0.0FA	5	141	3329		6367		7483		
NC:6.5:0.0FA	1	145	2930		4867		6764		
NC:6.5:0.0FA	1	145	2763	2846	4894	4866	6625	6721	615
NC:6.5:0.0FA	1	145	2844		4838		6773		
NC:6.5:30FA	9	144	1727		3339		5103		
NC:6.5:30FA	9	144	1924	1852	3403	3353	4949	5027	532
NC:6.5:30FA	9	144	1904		3318		5030		
NC:6.0:30FA	22	145	1436		3366		5091		
NC:6.0:30FA	22	145	1359	1421	3423	3261	5341	5228	542
NC:6.0:30FA	22	145	1467		2995		5252		
SCC:6.0:30FA	18	142	1964		4124		6284		
SCC:6.0:30FA	18	142	1961	1959	3998	4040	6202	6194	590
SCC:6.0:30FA	18	142	1953		3998		6095		

Note: Cylinder Size: 4x8 inch

Table AV.4: Compressive Strength test data (Continued)

Mix ID	Trial #	Unit Weight (pcf)	56 day break Strength	Average
SCC6.5:30FA	13	146	9230	
SCC6.5:30FA	13	146	9257	9013
SCC:6.5:30FA	13	146	8552	
SCC:6.5:0.0FA	5	141	8657	
SCC:6.5:0.0FA	5	141	8835	8807
SCC:6.5:0.0FA	5	141	8930	
NC:6.5:0.0FA	1	145	7391	
NC:6.5:0.0FA	1	145	7453	7439
NC:6.5:0.0FA	1	145	7474	
NC:6.5:30FA	9	144	6152	
NC:6.5:30FA	9	144	6232	6231
NC:6.5:30FA	9	144	6308	
NC:6.0:30FA	22	145	6370	
NC:6.0:30FA	22	145	6296	6253
NC:6.0:30FA	22	145	6094	
SCC:6.0:30FA	18	142	7566	
SCC:6.0:30FA	18	142	7336	7555
SCC:6.0:30FA	18	142	7765	

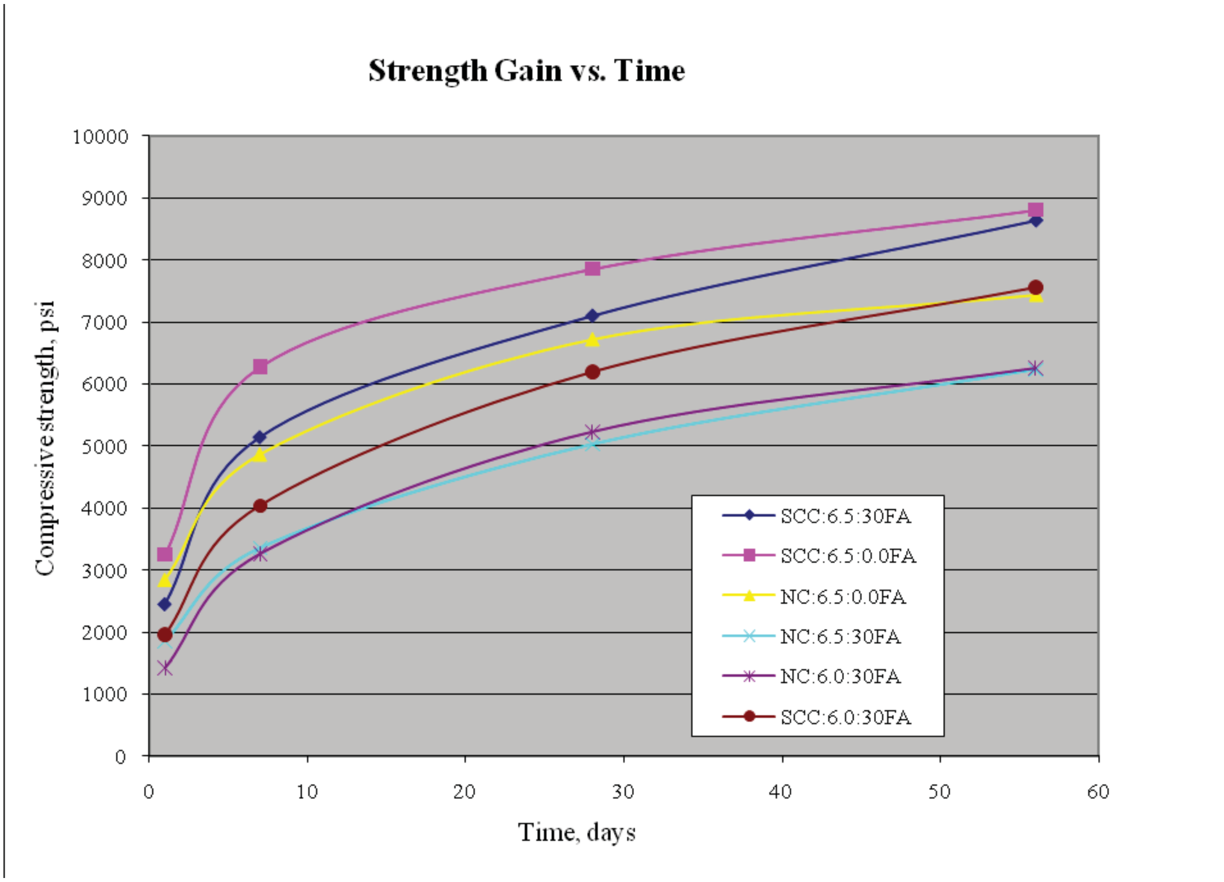

Figure AV.2: Compressive Strength gain vs. time

Table AV.5: Modulus of Rupture test data

ASTM C293-02: Modulus of Rupture Test Data											
Mix ID	Trial	P (lbs)	b (in)	d (in)	L	MOR, psi	Average	fc’	(σ-σ̄)^2	SD	COV
SCC:6.5:0.0FA	7	8787.20	6.00	6.19	18.00	1032.84			1042.02		
SCC:6.5:0.0FA	7	9004.30	5.94	5.94	18.00	1161.46	1065	7858.33	9280.82	69.34	6.51%
SCC:6.5:0.0FA	7	8008.50	6.00	6.00	18.00	1001.06			4103.26		
NC:6.5:0.0FA	3	7331.70	6.00	6.00	18.00	916.46			29.89		
NC:6.5:0.0FA	4	8129.90	6.13	6.31	18.00	899.37	911	6720.53	135.06	8.22	0.90%
NC:6.5:0.0FA	3	8283.00	6.00	6.38	18.00	917.15			37.87		
SCC:6.5:30FA	14	NA, machine malfunction									
SCC:6.5:30FA	16	7052.10	6.13	6.00	18.00	863.52	862	7094.44	2.63	1.32	0.15%
SCC:6.5:30FA	16	7172.00	6.00	6.13	18.00	860.28			2.63		
NC6.5:30FA	11	6636.60	6.00	6.00	18.00	829.58			608.65		
NC6.5:30FA	11	6815.00	6.25	6.00	18.00	817.80	854	5027.07	1328.30	43.48	5.09%
NC6.5:30FA	9	7631.20	6.00	6.13	18.00	915.36			3735.26		
SCC:6.0:30FA	20	6963.60	6.13	6.00	18.00	852.69			870.57		
SCC:6.0:30FA	19	7057.10	6.00	6.00	18.00	882.14	882	6193.83	0.00	24.11	2.73%
SCC:6.0:30FA	21	7294.00	6.00	6.00	18.00	911.75			873.73		
NC:6.0:30FA	11	7122.00	6.13	6.00	18.00	872.08			11.98		
NC:6.0:30FA	11	6972.80	6.25	5.94	18.00	854.44	876	5227.82	445.18	18.80	2.15%
NC:6.0:30FA	9	7051.60	6.00	5.94	18.00	900.10			603.25		
Note: Specimen Age = 28 Days											

Table AV.6: Modulus of Rupture test data

Mix ID	fc' (psi)	MOR (psi)	α
SCC:6.5:0.0FA	7858	1065.12	12.02
NC:6.5:0.0FA	6721	910.99	11.11
SCC:6.5:30FA	7568	861.90	9.91
NC:6.5:30FA	5027	854.25	12.05
SCC:6.0:30FA	6194	882.19	11.21
NC:6.0:30FA	5228	875.54	12.11

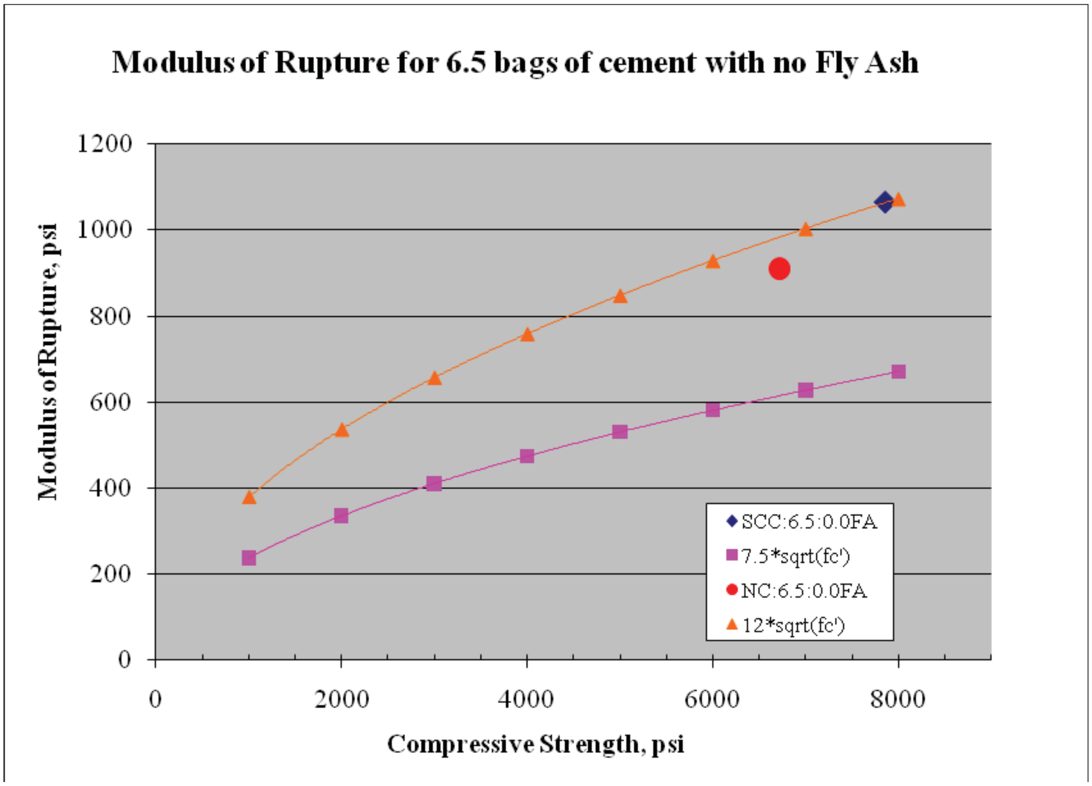

Figure AV.3: Modulus of Rupture for 6.5 bags of cement with no Fly Ash

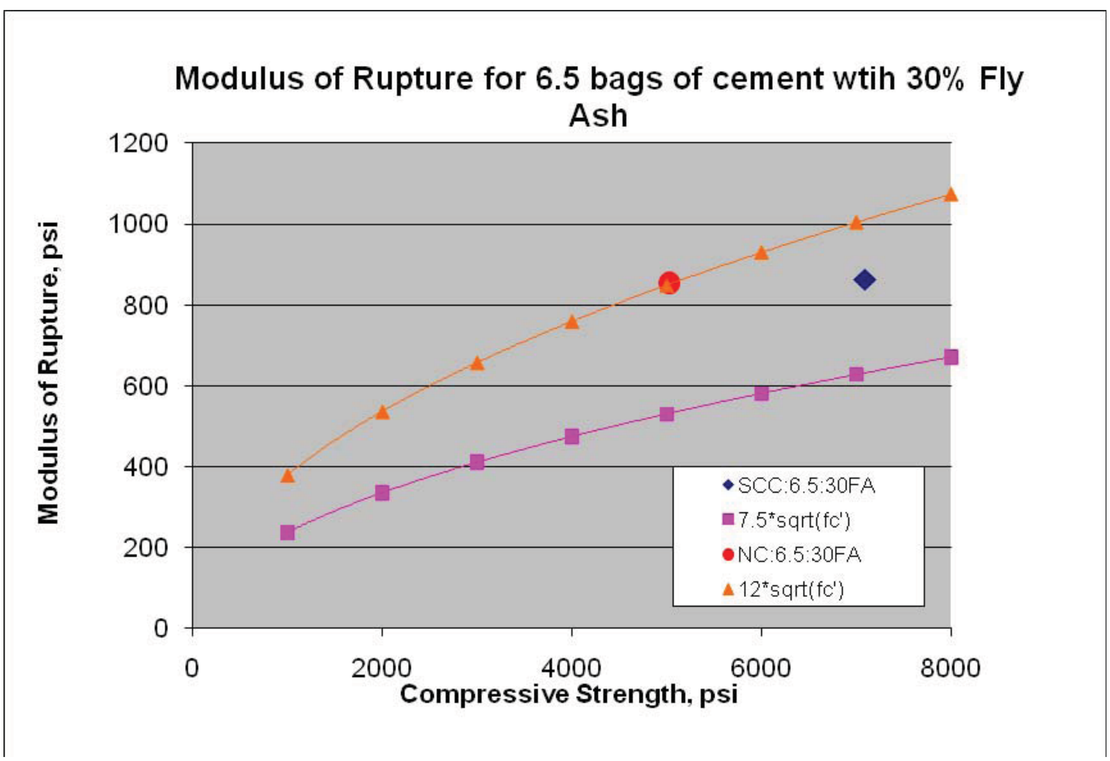

Figure AV.4: Modulus of Rupture for 6.5 bags of cement with 30% Fly Ash

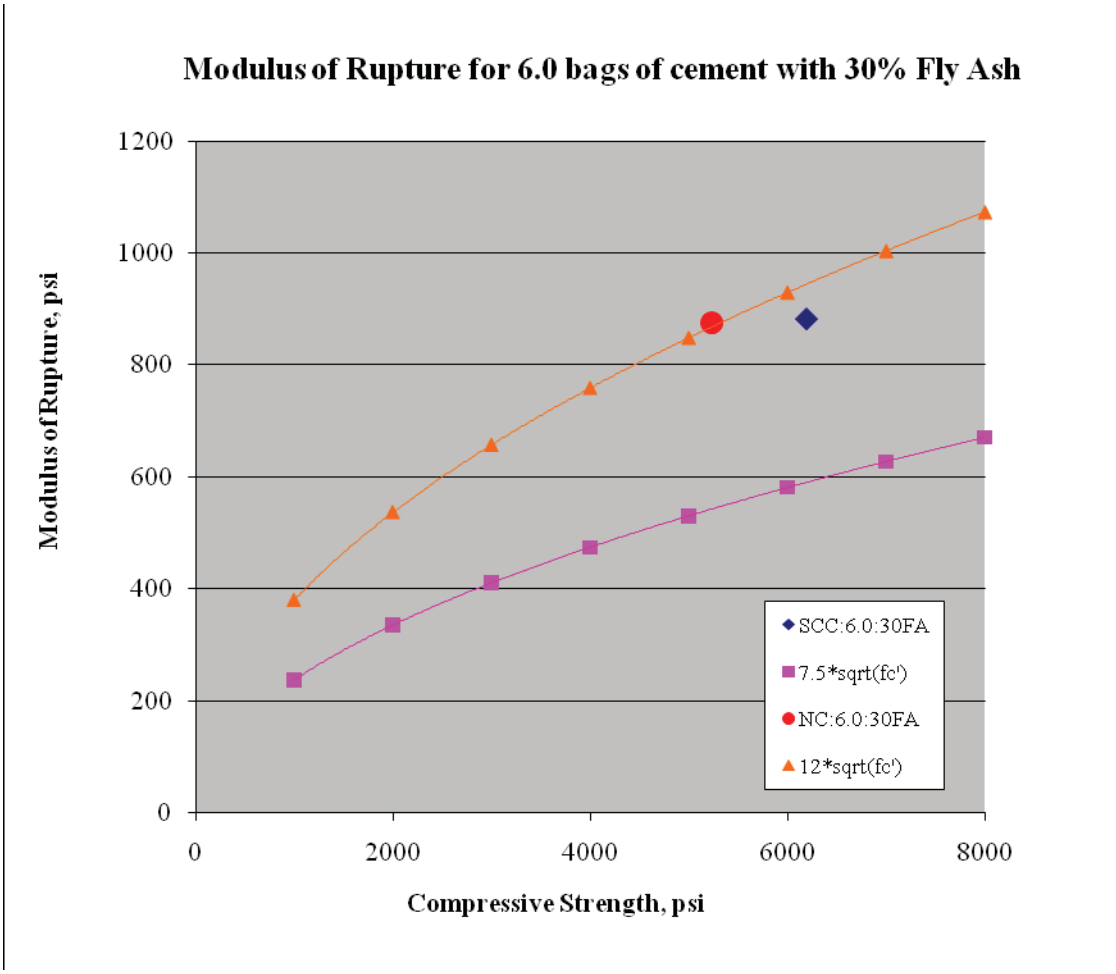

Figure AV.5: Modulus of Rupture for 6 bags of cement with 30% Fly Ash

Table AV.7: Modulus of Elasticity test data for SCC:6.5:0.0FA

SCC:6.5:0.0FA

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.98	147.59	213716
P (lbs)	Deflection	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
12900	0.001	0.0000625	456.2	4367.5	5144.5
20480	0.0019	0.00011875	724.3		
30000	0.0031	0.00019375	1061.0		
40000	0.00425	0.000265625	1414.7		
51500	0.00555	0.000346875	1821.4		
60300	0.0069	0.00043125	2132.7		
70400	0.00835	0.000521875	2489.9		
80500	0.00965	0.000603125	2847.1		
90600	0.01105	0.000690625	3204.3		
100500	0.01235	0.000771875	3554.5		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.98	147.59	213716
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10200	0.00095	0.000059375	360.8	4579.5	5144.5
20280	0.0021	0.00013125	717.3		
30400	0.00335	0.000209375	1075.2		
40400	0.00455	0.000284375	1428.9		
50500	0.00585	0.000365625	1786.1		
60500	0.0071	0.00044375	2139.7		
71300	0.0085	0.00053125	2521.7		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	29.09	148.15	210143
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10400	0.00075	0.000046875	367.8	5926.9	5130.3
20000	0.0019	0.00011875	707.4		
30500	0.00235	0.000146875	1078.7		
40000	0.0032	0.0002	1414.7		
50000	0.0042	0.0002625	1768.4		
60000	0.00525	0.000328125	2122.1		
70000	0.00625	0.000390625	2475.7		
80000	0.0072	0.00045	2829.4		
90000	0.00835	0.000521875	3183.1		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.922	147.30	215773
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10400	0.0012	0.000075	367.8	5017.3	5153.6
20000	0.00225	0.000140625	707.4		
30500	0.00345	0.000215625	1078.7		
40000	0.00455	0.000284375	1414.7		
50000	0.00575	0.000359375	1768.4		
60000	0.00685	0.000428125	2122.1		
70000	0.008	0.0005	2475.7		
80000	0.00905	0.000565625	2829.4		

Avg MOE	5174.6
Avg ACI MOE	5142.8

Table AV.8: Modulus of Elasticity test data for SCC:6.5:30FA

SCC:6.5:30FA

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.92	147.29	176977
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10000	0.00105	0.000065625	353.7	4491.1	4666.9
20000	0.00225	0.000140625	707.4		
30000	0.0035	0.00021875	1061.0		
40000	0.00475	0.000296875	1414.7		
50000	0.00605	0.000378125	1768.4		
60000	0.00735	0.000459375	2122.1		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lbs)
8	0.20	28.27	28.76235	146.49	167916
P (lbs)	deflection (in)	delta/guage (in/in)	stress (psi)	Measure MOE (ksi)	ACI MOE (ksi)
12900	0.00095	0.000059375	456.2	5076.8	4508.7
20990	0.00185	0.000115625	742.4		
31000	0.003	0.0001875	1096.4		
40000	0.00405	0.000253125	1414.7		
50000	0.00505	0.000315625	1768.4		
60000	0.0062	0.0003875	2122.1		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	29.1205	148.31	161969
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measure MOE (ksi)	ACI MOE (ksi)
10000	0.00055	0.000034375	353.7	5052.5	4511.1
20000	0.0017	0.00010625	707.4		
31468	0.00285	0.000178125	1113.0		
41000	0.0041	0.00025625	1450.1		
50000	0.00505	0.000315625	1768.4		
60000	0.00615	0.000384375	2122.1		

Avg MOE	4873.5
Avg ACI MOE	4562.3

Table AV.9: Modulus of Elasticity test data for SCC:6.0:30FA

SCC:6.0:30FA

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.28	144.03	167394
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksI)	ACI MOE (ksi)
11494	0.0015	0.00009375	406.5	5435.4	4389.0
20000	0.00235	0.000146875	707.4		
30000	0.0035	0.00021875	1061.0		
40000	0.0043	0.00026875	1414.7		
50000	0.00535	0.000334375	1768.4		
60000	0.00655	0.000409375	2122.1		

Effective Length (in	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.3	144.13	166963
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10000	0.00105	0.000065625	353.7	4563.6	4388.0
20000	0.00205	0.000128125	707.4		
30000	0.0033	0.00020625	1061.0		
40000	0.00445	0.000278125	1414.7		
50000	0.00575	0.000359375	1768.4		
60000	0.00725	0.000453125	2122.1		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lbs)	Unit Weight	Failure (lb)
8	0.20	28.27	28.3	144.13	172804
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10000	0.00095	0.000059375	353.7	5774.3	4464.1
20000	0.0018	0.0001125	707.4		
30000	0.00275	0.000171875	1061.0		
40000	0.00375	0.000234375	1414.7		
50000	0.00475	0.000296875	1768.4		
60000	0.00585	0.000365625	2122.1		

Avg MOE	5257.8
Avg ACI MOE	4413.7

Table AV.10: Modulus of Elasticity test data for NC:6.5:0.0FA

NC:6.5:0.0FA					
Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lbs)	Unit Weight	Failure (lb)
8	0.20	28.27	28.5565	145.44	167151
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksI)
10200	0.0009	0.00005625	360.8	5163.2	4450.3
20000	0.00205	0.000128125	707.4		
30000	0.0031	0.00019375	1061.0		
40000	0.0041	0.00025625	1414.7		
50000	0.00525	0.000328125	1768.4		
60000	0.0062	0.0003875	2122.1		
70000	0.0073	0.00045625	2475.7		
80000	0.00855	0.000534375	2829.4		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.5795	145.55	147885
P (lbs)	Deflection (in)	delta guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10000	0.0006	0.0000375	353.7	5246.6	4191.0
20000	0.0016	0.0001	707.4		
30000	0.0028	0.000175	1061.0		
40000	0.0039	0.00024375	1414.7		
50000	0.00495	0.000309375	1768.4		
60000	0.00605	0.000378125	2122.1		
70000	0.00715	0.000446875	2475.7		
80000	0.00815	0.000509375	2829.4		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.5395	145.35	160457
P (lbs)	Deflection	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10200	0.0008	0.00005	360.8	4072.0	4356.3
20000	0.0023	0.00014375	707.4		
30000	0.00355	0.000221875	1061.0		
40000	0.0049	0.00030625	1414.7		
50000	0.0061	0.00038125	1768.4		
60000	0.00745	0.000465625	2122.1		
70000	0.00895	0.000559375	2475.7		
80000	0.0105	0.00065625	2829.4		

Avg MOE	4827.3
Avg ACI MOE	4332.5

Table AV.11: Modulus of Elasticity test data for NC:6.5:30FA

NC:6.5:30FA					
Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.566	145.49	140997.00
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10000	0.0012	0.000075	353.7	5239.7	4089.3
20000	0.00255	0.000159375	707.4		
30000	0.0038	0.0002375	1061.0		
40000	0.00495	0.000309375	1414.7		
50000	0.00575	0.000359375	1768.4		
60000	0.0066	0.0004125	2122.1		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.566	145.49	145314.00
P (lbs)	Deflection (in)	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
12200	0.00135	0.000084375	431.5	4850.4	4151.5
20000	0.0023	0.00014375	707.4		
31200	0.00365	0.000228125	1103.5		
42300	0.00495	0.000309375	1496.1		
50300	0.00575	0.000359375	1779.0		
60200	0.00695	0.000434375	2129.1		

Avg MOE	5045.1
Avg ACI MOE	4120.4

Table AV.12: Modulus of Elasticity test data for NC:6.0:30FA

NC:6.0:30FA

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	29.42	149.83	149774
P (lbs)	Deflection	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
10000	0.00085	0.000053125	353.7	4755.3	4405.1
20000	0.00255	0.000159375	707.4		
30000	0.00425	0.000265625	1061.0		
40000	0.00425	0.000265625	1414.7		
50000	0.0055	0.00034375	1768.4		
60000	0.0068	0.000425	2122.1		

Effective Length (in)	Volume (ft^3)	Area (in^2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	28.879	147.08	147813
P (lbs)	Deflection	delta/guage (in/in)	Dtress (psi)	Measure MOE (ksi)	ACI MOE (ksi)
10000	0.0009	0.00005625	353.6776513	4130.54	4256.0082
20000	0.00215	0.000134375	707.3553026		
30000	0.00345	0.000215625	1061.032954		
43492	0.00535	0.000334375	1538.214841		
50000	0.0064	0.0004	1768.388257		
60000	0.00775	0.000484375	2122.065908		

Effective Length (in)	Volume (ft3)	Area (in2)	Weight (lb)	Unit Weight	Failure (lb)
8	0.20	28.27	29.176	148.59	144987
P (lbs)	Deflection	delta/guage (in/in)	Stress (psi)	Measured MOE (ksi)	ACI MOE (ksi)
11000	0.0011	0.00006875	389.0	5899.6	4280.3
20000	0.00185	0.000115625	707.4		
30000	0.00275	0.000171875	1061.0		
40000	0.0037	0.00023125	1414.7		
50000	0.0047	0.00029375	1768.4		
60000	0.0058	0.0003625	2122.1		

Avg MOE	4928.5
Avg ACI MOE	4313.8

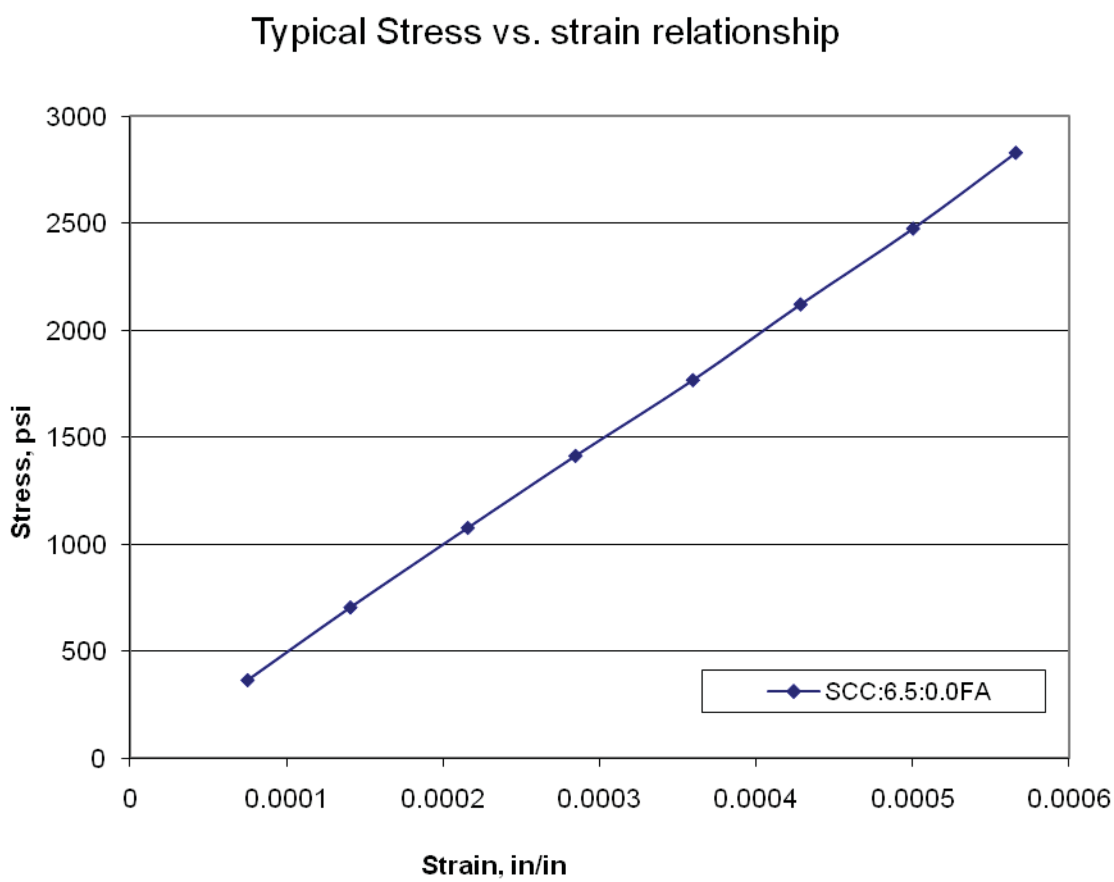

Figure AV.6: Stress vs. strain relationship

Table AV.13: Percent difference between measured and calculated MOE

Specimen ID	Average Measured MOE, KSI	Avg. ACI Calculated MOE, KSI	% difference
SCC:6.5:0.0FA	5174.566511	5142.808948	0.62%
NC:6.5:0.0FA	4827.291084	4332.529246	11.42%
SCC:6.5:30FA	4873.490904	4562.264803	6.82%
NC:6.5:30FA	5045.052635	4120.39392	22.44%
SCC:6.0:30FA	5257.771262	4413.659323	19.12%
NC:6.0:30FA	4928.505302	4313.806681	14.25%

Table AV.14: Drying Shrinkage test data

Mix Design ID	Sample number	Initial Length (in)	Length after 30 min Lime bath (in)	7 day length (in)	14 day length (in)	28 day length (in)	% Length Change at 28 days	Avg
NC:6.5:0.0FA	1	11.6165	11.616	11.6140	11.6150	11.6130	-0.03%	
NC:6.5:0.0FA	2	11.4170	11.4185	11.4195	11.4160	11.4145	-0.04%	-0.03%
NC:6.5:0.0FA	3	11.5230	11.523	11.5210	11.5200	11.5190	-0.03%	
SCC:6.5:0.0FA	1	11.5045	11.505	11.5035	11.4995	11.4980	-0.06%	
SCC:6.5:0.0FA	2	11.6240	11.622	11.6225	11.6210	11.6205	-0.01%	-0.04%
SCC:6.5:0.0FA	3	11.6055	11.606	11.6030	11.6015	11.6015	-0.04%	
NC:6.5:30FA	1	11.6180	11.6175	11.6165	11.6150	11.6140	-0.03%	
NC:6.5:30FA	2	11.5326	11.532	11.5305	11.5280	11.5280	-0.03%	-0.03%
NC:6.5:30FA	3	11.6395	11.64	11.6395	11.6370	11.6375	-0.02%	
SCC:6.0:30FA	1	14.8565	14.8565	14.8540	14.8540	14.8550	-0.01%	
SCC:6.0:30FA	2	11.2585	11.2585	11.2780	11.2765	11.2770		-0.02%
SCC:6.0:30FA	3	11.4065	11.4095	11.4080	11.4070	11.4050	-0.04%	
NC:6.0:30:FA	1	11.4330	11.4335	11.4330	11.4320	11.4325	-0.01%	
NC:6.0:30:FA	2	11.4545	11.4545	11.4510	11.4505	11.4505	-0.03%	-0.02%
NC:6.0:30:FA	3	11.4955	11.5005	11.4980	11.4965	11.4975	-0.03%	
SCC6.5:30FA	1	11.4515	11.4515	11.4505	11.4485	11.4480	-0.03%	
SCC6.5:30FA	2	11.529	11.529	11.5300	11.5285	11.5270	-0.02%	-0.07%
SCC6.5:30FA	3	11.5090	11.53	11.5135	11.5125	11.5125	-0.15%	

Table AV.14: Drying Shrinkage test data (continued)

Mix Design ID	Sample number	32 days length (in)	56 day length (in)	% Length Change at 56 days	Avg	112 day length (in)	% Length Change at 112 days	Avg
NC:6.5:0.0FA	1	11.6140	11.6120	-0.03%		11.6115	-0.04%	
NC:6.5:0.0FA	2	11.4180	11.4135	-0.04%	-0.05%	11.4140	-0.04%	-0.04%
NC:6.5:0.0FA	3	11.5200	11.5160	-0.06%		11.5175	-0.05%	
SCC:6.5:0.0FA	1	11.5030	11.5005	-0.04%		11.4995	-0.05%	
SCC:6.5:0.0FA	2	11.6185	11.6195	-0.02%	-0.04%	11.6200	-0.02%	-0.04%
SCC:6.5:0.0FA	3	11.6030	11.6005	-0.05%		11.6000	-0.05%	
NC:6.5:30FA	1	11.6155	11.6130	-0.04%		11.6100	-0.06%	
NC:6.5:30FA	2	11.5280	11.5270	-0.04%	-0.04%	11.5265	-0.05%	-0.05%
NC:6.5:30FA	3	11.6375	11.6365	-0.03%		11.6360	-0.03%	
SCC:6.0:30FA	1	14.8565	14.8530	-0.02%		14.8525	-0.03%	
SCC:6.0:30FA	2	11.2560	11.2760		-0.04%	11.2715	0.12%	-0.03%
SCC:6.0:30FA	3	11.4085	11.4040	-0.05%		11.4060	-0.03%	
NC:6.0:30:FA	1	11.4365	11.4135	-0.18%		11.4305	-0.03%	
NC:6.0:30:FA	2	11.4540	11.4475	-0.06%	-0.09%	11.4480	-0.06%	-0.04%
NC:6.0:30:FA	3	11.4950	11.4960	-0.04%		11.4950	-0.05%	
SCC6.5:30FA	1	11.4490	11.4480	-0.03%		11.4460	-0.05%	
SCC6.5:30FA	2	11.5275	11.5265	-0.02%	-0.08%	11.5260	-0.03%	-0.08%
SCC6.5:30FA	3	11.5105	11.5075	-0.20%		11.5100	-0.17%	

Table AV.15: Percent length change at 28, 56, and 112 Days

Mix ID	Avg. Length change at 28 days (%)	Avg. Length change at 56 days (%)	Avg. Length change at 112 days (%)
NC:6.5:0.0FA	-0.03%	-0.05%	-0.04%
SCC:6.5:0.0FA	-0.04%	-0.04%	-0.04%
NC:6.5:30FA	-0.03%	-0.04%	-0.05%
SCC6.5:30FA	-0.07%	-0.08%	-0.03%
NC:6.0:30:FA	-0.02%	-0.09%	-0.04%
SCC:6.0:30FA	-0.02%	-0.04%	-0.08%

Table AV.16: Rapid Chloride Ion Permeability test data

Mix ID	Total Coulombs	Average	$(\sigma-\bar{\sigma})^2$	$\sum(\sigma-\bar{\sigma})^2$	Std Dev	COV	Rating Based On ASTM C 1202
SCC:6.5:0.0FA	2450		57600				
	2270	2210	3600	151200	224	10%	Moderate
	1910		90000				
SCC:6.5:30FA	1340		100278				
T19	2580	1657	852544	1320867	813	49%	Low
T26	1050		368044				
SCC:6.0:30FA	1630		44100				
Top	1450	1420	900	102600	185	13%	Low
Bot	1180		57600				
NC:6.5:0.0FA	2170		1111				
	1750	2137	149511	275467	303	14%	Moderate
	2490		124844				
NC:6.5:30FA	1120		49878				
	900	897	11	101267	225	25%	Negligible
	670		51378				
NC:6.0:30FA	1240		23511				
	1130	1087	1878	64067	146	13%	Low
	890		38678				

Table AV.17: Rapid Chloride Ion Permeability summary test data

ASTM C 1202: Rapid Chloride Ion Permeability							
Mix ID	**Coulombs**	**Coulombs**	**Coulombs**	**Avg Total Coulombs**	**Std Dev**	**COV**	**Rating Based On ASTM C 1202**
SCC:6.5:0.0FA	2450	2270	1910	2210	224	10.2%	**Moderate**
SCC:6.5:30FA	1340	2580	1050	1657	813	49.1%	**Low**
SCC:6.0:30FA	1630	1450	1180	1420	185	13.0%	**Low**
NC:6.5:0.0FA	2170	1750	2490	2137	303	14.2%	**Moderate**
NC:6.5:30FA	1120	900	670	897	225	25.1%	**Low**
NC:6.0:30FA	1240	1130	890	1087	146	13.4%	**Low**

Table AV.18: Rapid chloride ion permeability test data without outliers

Mix ID	Total Coulombs	Average	$(\sigma-\bar{\sigma})^2$	$\sum(\sigma-\bar{\sigma})^2$	Std Dev	COV	Rating Based On ASTM C 1202
SCC:6.5:0.0FA	2450		57600				
	2270	2210	3600	151200	224	10.2%	Moderate
	1910		90000				
SCC:6.5:30FA	1340		21025				
		1195		42050	145	12.1%	Low
T19	2580						
T26	1050		21025				
SCC:6.0:30FA	1630		44100				
Top	1450	1420	900	102600	185	13.0%	Low
Bot	1180		57600				
NC:6.5:0.0FA	2170		1111				
	1750	2137	149511	275467	303	14.2%	Moderate
	2490		124844				
NC:6.5:30FA	1120		12100				
	900	1010	12100	24200	110	10.9%	Negligible
	670						
NC:6.0:30FA	1240		23511				
	1130	1087	1878	64067	146	13.4%	Low
	890		38678				

Table AV.19: Rapid chloride ion permeability test data without outliers

Mix ID	**Coulombs**	**Coulombs**	**Coulombs**	**Avg Total Coulombs**	**Std Dev**	**COV**	**Rating Based On ASTM C 1202**
SCC:6.5:0.0FA	2450	2270	1910	2210	224	10.2%	**Moderate**
SCC:6.5:30FA	1340	2580	1050	1195	145	12.1%	**Low**
SCC:6.0:30FA	1630	1450	1180	1420	185	13.0%	**Low**
NC:6.5:0.0FA	2170	1750	2490	2137	303	14.2%	**Moderate**
NC:6.5:30FA	1120	900	670	1010	110	10.9%	**Low**
NC:6.0:30FA	1240	1130	890	1087	146	13.4%	**Low**

Table AV.20: Linear Traverse test data

Trial #	Mix ID	Air Void Content	% Entrained (≤ 0.04")	% Entrapped (≥ 0.04")	Spacing Factor, (in)	Consistent With Freeze/Thaw Resistance?
5	SCC:6.5:0.0FA	5	3.4	1.6	0.01	no
15	SCC:6.5:30FA	5.4	5.1	0.3	0.006	yes
18	SCC:6.0:30FA	5.8	4.8	1	0.01	no
2	NC:6.5:0.0FA	5.7	4.7	1	0.005	yes
22	NC:6.5:30FA	4.6	4	0.6	0.005	yes
25	NC:6.0:30FA	3.5	3.2	0.3	0.005	yes
Freeze Thaw Limit is set by ACI 201.2						
Max Spacing Factor, to be Freeze/Thaw Resistant					0.008	in

Table AV.21: Splitting Tensile Strength test data

Mix ID	Trial	P (lb)	l (in)	diameter (in)	SPTS	Average	$(\sigma-\bar{\sigma})^2$	SD	COV (%)
SCC:6.5:0.0FA	7	65274.00	12	6	577.15		97.31		
SCC:6.5:0.0FA	7	63323.00	12	6	559.90	587.01	735.24	27.08	4.61
SCC:6.5:0.0FA	7	70572.00	12	6	623.99		1367.52		
NC:6.5:0.0FA	3	52629.00	12	6	465.34		720.77		
NC:6.5:0.0FA	4	53409.00	12	6	472.24	492.19	398.02	33.21	6.75
NC:6.5:0.0FA	3	60958.00	12	6	538.99		2190.00		
SCC:6.5:30FA	16	43761.00	12	6	386.93		7347.86		
SCC:6.5:30FA	15	63760.00	12	6	563.76	472.65	8301.09	72.29	15.29
SCC:6.5:30FA	15	52846.00	12	6	467.26		29.06		
NC:6.5:30FA	11	54236.00	12	6	479.55		52.06		
NC:6.5:30FA	11	52613.00	12	6	465.20	472.34	50.91	5.86	1.24
NC:6.5:30FA	9	53411.00	12	6	472.26		0.01		
NC:6.0:30FA	11	51574.00	12	6	456.01		69.42		
NC:6.0:30FA	11	46829.00	12	6	414.06	447.68	1130.50	24.76	5.53
NC:6.0:30FA	9	53492.00	12	6	472.97		639.63		
SCC:6.0:30FA	11	61347.00	12	6	542.43		1026.96		
SCC:6.0:30FA	11	68547.00	12	6	606.09	574.47	999.56	25.99	4.52
SCC:6.0:30FA	9	65020.00	12	6	574.90		0.19		

Table AV.22: Splitting Tensile Strength test data

Mix ID	fc' (psi)	Measured SPTS	β=6	β
SCC:6.5:0.0FA	7858	587.01	531.88	6.62
NC:6.5:0.0FA	6721	492.19	491.87	6.00
SCC:6.5:30FA	7568	472.65	505.37	5.43
NC:6.5:30FA	5027	472.34	425.41	6.66
SCC:6.0:30FA	6194	574.47	472.21	7.30
NC:6.0:30FA	5228	447.68	433.82	6.19

Table AV.23: Pullout test data

Trial	Mix ID	fc', psi	Max Load, lb	Notes	Avg Strength, psi
8	SCC:6.5:0.0FA	8596	12720	Pullout bar was not straight	8357
8	SCC:6.5:0.0FA	8118			
6	SCC:6.5:0.0FA	7044	22973	2.75" TC	7163.5
6	SCC:6.5:0.0FA	7283	22973		
7	SCC:6.5:0.0FA	7800	21880	2.75" TC	7481.5
7	SCC:6.5:0.0FA	7163	21880		
2	NC:6.5:0.0FA	6012	16960		5949
2	NC:6.5:0.0FA	5886	16960		
4	NC:6.5:0.0FA	7163	19147		7044
4	NC:6.5:0.0FA	6925	19147		
3	NC:6.5:0.0FA	6168	16960		5909.5
3	NC:6.5:0.0FA	5651	16960		
14	SCC:6.5:30FA	5174	15264	2.75" TC	5492
14	SCC:6.5:30FA	5810	15264		
16	SCC:6.5:30FA	5571	15264		5710.5
16	SCC:6.5:30FA	5850	15264		
15	SCC:6.5:30FA	5482	19147	2.75" TC	5407.5
15	SCC:6.5:30FA	5333	19147		
11	NC:6.5:30FA	5174	16960		5174
11	NC:6.5:30FA	5174	16960		
12	NC:6.5:30FA	5134	22973		5134

12	NC:6.5:30FA	5134	22973		
10	NC:6.5:30FA	5731	15264		5313
10	NC:6.5:30FA	4895	15264		

Table AV.24: Pullout test data

Trial	Mix ID	fc', psi	Max Load, lb	Notes	Avg Strength, psi
T25	NC:6.0:30FA	5014	16960		5094
T25	NC:6.0:30FA	5174			
T24	NC:6.0:30FA	4895	14840		5034.5
T24	NC:6.0:30FA	5174			
T23	NC:6.0:30FA	5054	16112	2.625" top cover	5233
T23	NC:6.0:30FA	5412			
T20	SCC:6.0:30FA	6168	20786	3" top cover	6029
T20	SCC:6.0:30FA	5890			
T19	SCC:6.0:30FA	5651	16536	2.75" top cover	5691
T19	SCC:6.0:30FA	5731		2.75" top cover	
T21	SCC:6.0:30FA	5850	16960	2.75" top cover	5870
T21	SCC:6.0:30FA	5890			

Table AV.25: Pullout test data

Mix ID	Compressive strength (Air-Cured) (psi)	Max, Tensile Load (lbs)	As-Built Top Cover (in)	Average Compressive Strength (psi)	Average Pullout Strength (lbs)
SCC:6.5:0.0FA	7164	22973	2.75	7323	22426.5
SCC:6.5:0.0FA	7482	21880	2.75		
NC:6.5:0.0FA	5949	16960	2.625	6301	17689
NC:6.5:0.0FA	7044	19147	2.5		
NC:6.5:0.0FA	5910	16960	2.75		
SCC:6.5:30FA	5492	15264	2.75	5537	16558
SCC:6.5:30FA	5711	15264	2.5		
SCC:6.5:30FA	5408	19147	2.75		
NC:6.5:30FA	5174	16960	2.75	5207	18399
NC:6.5:30FA	5134	22973	2.5		
NC:6.5:30FA	5313	15264	2.5		
SCC:6.0:30FA	6029	20786	3	5863	18094
SCC:6.0:30FA	5691	16536	2.75		
SCC:6.0:30FA	5870	16960	2.75		
NC:6.0:30FA	5094	16960	2.5	5121	15752
NC:6.0:30FA	5035	14184	2.5		
NC:6.0:30FA	5233	16112	2.625		

Table AV.26: Average compressive strength and pullout strength

Mix design	Compressive Strength (psi)	Pullout Strength (lbs)
SCC:6.5:0.0FA	7323	22427
NC:6.5:0.0FA	6301	17689
SCC:6.5:30FA	5537	16558
NC:6.5:30FA	5207	18399
SCC:6.0:30FA	5863	18094
NC:6.0:30FA	5121	15752

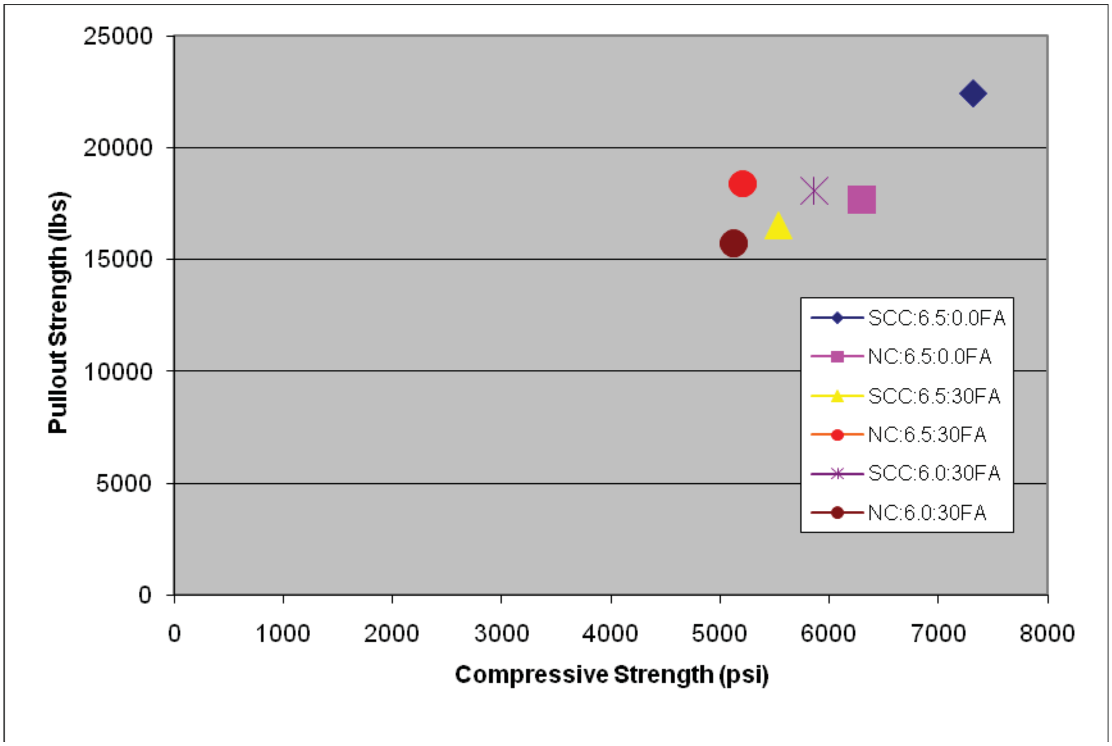

Figure AV.7: Compressive strength vs. pullout strength

Table AV.27: Pullout Test data

NC:6.0:30FA

Trial #	25		24		23	
Psi	Load	Slip "	Load	Slip "	Load	Slip "
250	4240	0	4240	0	4240	0
300	5088	0.03655	5088	0.0168	5088	0.0347
600	10176	0.1165	10176	0.06845	10176	0.08685
900	15264	0.1391	14840	0.1	16112	0.1154
1000	16960	0.182				

NC:6.5:0.0FA

Trial #	2		3		4	
Psi	Load	Slip "	Load	Slip "	Load	Slip "
250	4240	0	4240	0	4240	0
300	5088	0.028	5088	0.0155	5088	0.002
600	10176	0.04675	10176	0.04155	10176	0.018
900	15264	0.06655	15264	0.0636	15264	0.036
1000	16960	0.10735	16960	0.0809	16960	0.041
			19147	0.0822	19147	0.046

SCC:6.0:30FA

Trial #	20		19		21	
Psi	Load	Slip "	Load	Slip "	Load	Slip "
250	4240	0	4240	0	4240	0
300	5088	0.0311	5088	0	5088	0.06125
600	10176	0.0923	10176	0.0239	10176	0.108
900	15264	0.121	14840	0.0484	15264	0.1265
1000	16960	0.13	16536		16960	0.14
1100	19147	0.14				
1175	20786	NA				

SCC:6.5:30FA

Trial #	14		15		16	
Psi	Load	Slip "	Load	Slip "	Load	Slip "
250	4240	0	4240	0	4240	0
300	5088	0.0099	5088	0.0079	5088	0.00225
600	10176	0.04135	10176	0.03255	10176	0.03455
900	15264	0.0736	15264	0.056	15264	0.05
1000	16960	0.10735	16960	0.06245		
			19147	0.116		

SCC:6.5:30FA

Trial #	10		11		12	
Psi	Load	Slip "	Load	Slip "	Load	Slip "
250	4240	0	4240	0.00035	4240	0
300	5088	0.003	5088	0.00295	5088	0.01285
600	10176	0.003	10176	0.02	10176	0.05795
900	15264	0.039	15264	0.0478	15264	0.09
1000			16960	0.06	16960	0.1
1100			19147	0.116	19147	0.1128
1200					21333	0.1269
1275					22973	0.139

Appendix IV. Technology Transfer Program

The technology transfer workshops were intended to stimulate interest in concrete technology using SCC techniques. Attendees was expected to have a greater understanding of the potentials for solving problems where non-segregating mixes can be placed without vibration. Applications include tight spacing for rebar; difficult access situations; durable, strong, low W/C construction without segregation; improved surface aesthetic needs; cost savings in construction; and optimization of general consolidation. Projects which would typically use this type of SCC mix include water tanks, bridge abutments & decks, building floors and columns, precast, site cast/tilt up, and heavily reinforced RC sections. It was expected that the attendee will also have a better understanding of the general mix design process for SCC types of concrete plus general information on effective construction techniques.

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