

Construction Challenges of Cast-In-Place Self-Consolidating Concrete

Yaohua Deng and George Morcous, Ph.D., P.E.
University of Nebraska Lincoln
Omaha, NE 68182-0571

Self-Consolidating Concrete (SCC) is becoming more widely used in construction in recent years due to its favorable attributes, such as productivity improvements, reduced labor costs, improved work environment and safety, and improved product quality. The cast-in-place applications of SCC include bridges, buildings, drilled shafts and tunnel linings. Several challenges are associated with these applications, such as formwork pressure, pumpability, cross slope, and surface finish. This paper is a literature review of these challenges and presents the state-of-art studies and guidelines to address these challenges and improve the use of SCC in cast-in-place construction.

Key words: Self-Consolidating Concrete, Pumpability, Cross Slope, Surface Finish, Formwork Pressure.

Introduction

Developing a durable concrete was the main goal behind the development of Self-consolidating concrete (SCC) in 1988 in Japan. Durability-related problems frequently reported in concrete structures necessitated the development of a durable concrete that is less dependent on the quality of construction work (Okamura and Ouchi, 2003). According to the American Concrete Institute (ACI) Committee 237, SCC is defined as “a highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation”. Another definition according to the European Guidelines for SCC is “a concrete that is able to flow and consolidate under its own weight, completely fill the formwork even in the presence of dense reinforcement, whilst maintaining homogeneity and without the need for any additional compaction”. The main advantage of SCC include its:

- ability to achieve full compaction of concrete in areas that are very hard to reach because of complex formwork and/or dense reinforcement.
- consistency of quality due to adequacy and uniformity of concrete compaction, which results in more durable concrete and better surface finish
- significant reduction in construction time, labor cost, and noise pollution due to elimination of concrete vibration and minimization of concrete finishing operation.

Despite the significant advantages of SCC, its cast-in-place applications in North America has been very limited due to lack of design and construction guidelines and concerns about issues perceived to influence construction efficiency and structural integrity. The cast-in-place applications of SCC include bridges, buildings, drilled shafts and tunnel linings (Ouchi et al., 2003, Hodgson et al., 2005, Barragan et al., 2006, Nowak et al., 2007, Khayat et al., 2009). Ouchi et al. (2003) presented case studies of the applications of SCC in Japan and Europe, i.e., Ritto Bridge and Higashi-Oozu Viaduct in Japan, and the Sodra Lanken project in Sweden. It was stated that the SCC has high potential for wider structural applications in highway bridge construction. Hodgson et al. (2005) compared SCC with conventional drilled shaft concrete in an actual full-scale drilled shaft application and found SCC could be feasible for use in congested drilled shaft applications. Barragan et al. (2006) developed high strength SCC for application in tunnel linings in view of the high compressive loads on the tunnel, limited lining thickness, and heavy reinforcement. The application demonstrated that in-situ placing of concrete in tunnel linings can benefit significantly from the use of high strength SCC. Nowak et al. (2007) have developed a practical guide for the cast-in-place application of SCC in Nebraska, based on the experience gained from laboratory and full-scale tests. Several trial mixes were developed and tested at the Laboratory. Developed SCC was pumped in two concrete barriers and tests were performed to evaluate the impact of the delivery time, concrete temperature, and pouring method on basic SCC properties. Khayat et al. (2009) developed guidelines for the use of SCC in precast, prestressed concrete bridge elements. These guidelines address the selection of constituent materials, proportioning of concrete mixtures, testing methods, fresh and hardened concrete properties, production and quality control issues, and other aspects of SCC. Many of these recommendations can be adopted for cast-in-place applications of SCC.

Due to special requirements for SCC in its fresh state, the procedures for mix proportioning commonly used for normal concretes had to be modified. The SCC mix can be obtained by using a high powder content or by Viscosity Modifying Agents (VMA), or a combination of both, in addition to a higher dose of the superplasticizer as compared to ordinary concretes. Nowak et al. (2007) suggested 6 ksi SCC mix design to the Nebraska Department of Roads (NDOR) for construction of bridge diaphragms in Nebraska, as shown in Table 1.

Table 1. SCC Mix Design

Item	weight (*lb/cy*)	Admixtures (*oz/cy*)
I PF Cement	810	
Coarse 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

Construction challenges of cast-in-place SCC, such as formwork pressure, pumpability, cross slope, surface finish, which are crucial for the quality assurance of the concrete elements and on-site construction operations, need to be further investigated. This paper presents a literature survey on construction challenges of cast-in-place SCC and the state-of-art reports and guidelines dealing with those challenges.

Formwork Pressure

The formwork lateral pressure of SCC is generally higher than that of conventional vibrated concrete (CVC) mainly due to SCC's rheological feature such as low yield stress. Therefore, cast-in-place SCC requires more expensive and stronger formworks. Form work safety and economics are key issues to the application of SCC.

ACI committee 347 (2004) has discussed the maximum pressure generated by SCC and given recommendations as: "When working with mixtures using newly introduced admixtures that increase set time or slump characteristics, such as SCC, 'full liquid head' should be used until the effect on formwork is understood by measurement." Nasvik (2004) recommended that designing and building forms assuming full liquid head help to speed up the construction without restricting the place rate. When full liquid head is adopted for the design of form, the concrete is assumed to be in a liquid state along full height of the form. The lateral pressure is derived by the product of the full height of the concrete and its unit weight, i.e., 150 lb/ft^3. For example, a SCC placement with 16 ft height would produce lateral pressure of 2400 lb/ft^2 at the bottom of the form. Once the forms are designed to handle the full load, no restriction is given on rate of placement. Pumping SCC concrete into the bottom of a form is the best way to minimize entrapped air and bugholes (Note that bugholes result from the migration of entrapped air to the fresh concrete-form interface at the time of placement and consolidation), but lateral form pressure should be determined by 125% of full liquid head to account for pump pressures.

If the sensors are adopted to monitor the level of stiffness of SCC, the formwork and tie spacing for SCC can be designed by less than full liquid head. Several ways can be used to monitor the state of concrete and get more accurate data. The strain gauges can be glued to the ties along the members of the structure. The stresses on the ties are monitored to determine the stiffness of concrete, and the progression of initial set of concrete of the members can be thus obtained. However, the strain gauges cannot be reused for next measurement. Otherwise, surface pressure cells may be permanently mounted on the forms. This approach allow sensor and can be reused. In addition, another method which employs the use of using maturity meters is another way to map the initial set of concrete as it progresses up the members. These sensors are reusable and help to decide if the forms can safely be uninstalled (Nasvik, 2004).

The effect of binder type and content on the lateral pressure of SCC has been investigated by Assaad and Khayat (2005). Five binder types were incorporated at contents varying from 400 to 550 kg/m^3. The conclusion from test results was made as follows: (1) for a given binder content, the binder type significantly influenced the initial lateral pressure and rate of pressure drop with time. SCC made with 450 kg/m^3 of Type 10 CSA cement (Calcium Sulpho Aluminate cement) and no supplementary cementitious materials exhibited the highest initial pressure corresponding to 98% of hydrostatic pressure. Mixtures made with quaternary, binary, and ternary cements of similar content developed lower initial relative pressures of 95, 94, and 90%, respectively; (2) for a given binder type, the initial lateral pressure was found to increase with the binder content, which was attributed to the relatively lower coarse aggregate volume that reduces internal friction leading to greater lateral pressure. It is noted that the rate of pressure drop following casting is dependent on the degree of increase in cohesion. Therefore, an increase in binder content resulted in a greater rate of gain in cohesiveness and a sharper drop in lateral pressure with time; (3) the increase in the degree of thixotropy of SCC and Concrete-Equivalent Mortar (CEM) can lead to lower initial pressure. Besides, thixotropy determined using CEM mixtures should be used to estimate the rate of variation in lateral pressure rather than those determined from SCC mixtures. This is because the increase in thixotropy determined from concrete mixtures is highly affected by internal friction resulting from the presence of coarse aggregate, which can overshadow the development of cohesion resulting from the phase that controls the rate of pressure drop with time.

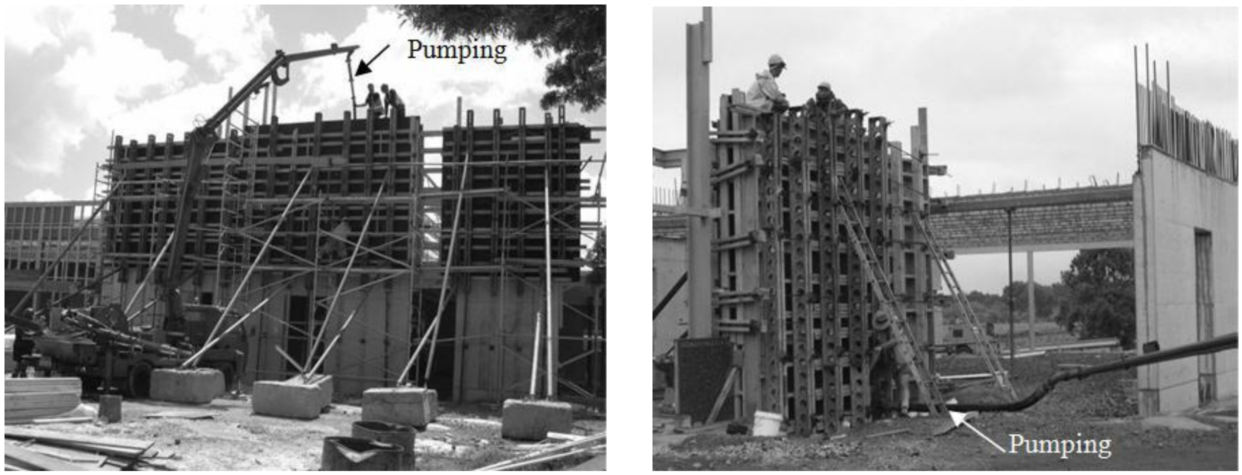
Gregori et al. (2008) found that formwork pressures less than hydrostatic are achievable. Higher pressures were associated with higher water/binder and casting rates. A reduction of formwork pressure up to 50% of the hydrostatic value was recorded with a casting rate of 23 ft/hour and a w/b of 0.32. The research data showed that incorporation of fly ash reduces SCC formwork pressure. A laboratory device is developed to describe the formwork pressure behavior of SCC and reduces the cost and time needed to conduct the same research on real structures. The effects of casting rate and mixture composition were studied by pressurizing a volume of material inside a cylinder and recording the lateral pressure evolution. Columns were measured 46 ft in height, two different casting rates were simulated and mixtures were designed using four different water-binder ratios (w/b) and different binder compositions.

Pumpability

Pumping is a very efficient and reliable method of placing concrete especially SCC due to its high flow ability and stability without mechanical vibration. Further, a SCC mix design with its higher fine content than the design of CVC makes it an ideal choice for pumping concrete. Pumpability can be defined as the ability of the concrete to be pumped without significant degradation of its fresh properties. Pumping SCC can be conducted from top or the bottom of the forms, as demonstrated by Khrapko (2007) in Figure 1.

In practice, SCC has been treated as a simple extension of CVC with respect to pumping. However, Freys et al. (2010) it has been clearly shown that the rheological properties and the mix design of SCC are different from those of CVC. A striking difference is the flow behavior in the pipes. The flow of CVC is a plug, surrounded by a lubricating layer, while flow of SCC is like a viscous fluid where the concrete volume is sheared inside the pipe. This makes the viscosity of SCC, length of pumping line, pumping pressure, and pipe diameter important parameters of pumpability. In addition, the behavior of SCC in bends is different due to the low yield stress of SCC. Due to the lower content of aggregate and better stability of SCC and its less proneness to internal water migration, blocking in the slick-line seldom occurs in case of SCC.

Pumping fresh concrete is influenced by time dependency of rheological properties of the concrete. This time dependency can be divided into two parts: the non-reversible part, being loss of workability and the reversible part, called thixotropy. Loss of workability can be neglected in some cases, when compared to the effect of thixotropy. Freys et al. (2009) found that no general test procedure had been commonly introduced to describe thixotropy of SCC. He also found, during high speed pumping, thixotropy can have an effect on stability/segregation, non-linear pressure distribution with the length of the pipes (at least in the upstream part) and creation of a very complicated velocity profile. Only one theory has taken into account the influence of thixotropy on both viscosity and yield stress: Hattori-Izumi theory, modified by Wallevik (2003). Viscosity can be described as a resistance to flow and yield stress is defined as a minimum force which is required to cause concrete to flow. This theory could provide a qualitative description of the behavior of SCC during pumping.



(a) **From the top** *(b)* **From the bottom**

Figure 1: Pumping SCC (Khrapko, 2007).

Interim SCC Guidelines by PCI (PCI SCC, 2004) gave the general requirement for pumping SCC: (1) On the basis of test placements, deposition locations should be selected and the optimal length of flow should be determined. Note that the length of the pumping line has influences on the flow characteristics of the material. (2) SCC mix should be continuously and timely transported to the site. Even though pumping helps to place concrete faster, it is still important to delivery and place concrete when SCC mix maintains its ability of self-compactability. (3) the pumping operation can be optimized by proper sizing of lines and equipment. The concrete can move at a specific flow rate when a line pressure can be established accordingly. Several factors influencing line pressure and flow rate are listed as:

- Pumping rate
- Line diameter
- Horizontal and vertical distance
- Reducers
- Number of bends
- Amount of flexible hose used.

Interim SCC Guidelines by PCI (PCI SCC, 2004) gave the instruction for prevention of blockage: (1) Piston pumps are generally used to place large quantities of fresh concrete; (2) blockage might happen if there is leakage at joints or the pumping has stop for a while. (3) In order to prevent blockage, the pump network must be concrete tight, fresh concrete should have minimal segregation, a sufficient volume of cement grout is pumped before fresh concrete can be pumped and time to initial set needs to be longer than placement time. (4) Three main causes of pump line blockage are listed as:

- Mix Design: poorly graded sand will cause the mix to bleed, which cause water to bleed through small channels formed due to voids in the sand. Thus, segregation occurs. Mixing for SCC should be sufficient to avoid segregation of mix. For instance, coarse aggregate must have a full coating of grout to lubricate the mix.
- Pipe Line Leakage: Due to existence of old concrete or defective couplings, gaskets, or weld collars pipes which can contribute to grout loss, improper cleaning may cause blockages.
- Operator Error: The most common error is from inexperienced operators.

Cross Slope

Cross slopes, which are typically 2%, are an inevitable part of roadway geometry as they provide drainage thus reducing the risk of slippery pavements. Super-elevations are also needed on horizontal curves to allow higher vehicle speeds. Super-elevation tilts the roadway to help offset centripetal forces developed as the vehicle goes around a curve. Along with friction, it keeps a vehicle from going off the road. Because of its low flow ability, conventional pavement concrete is generally stiff and has no problem for creating gentle slopes. However, it could be a great challenge for highly flowable concrete or SCC to create any slope since SCC is self-flowing and self-leveling. To create 2% cross slope for pavement construction, bridge decks and approach slabs, non-conventional SCC need to be used.

Based on the current state-of-the-knowledge, Ouchi et al (2003) found a bridge deck with a slope of 2% could be accomplished and proposed the following workability specifications for SCC are achievable through proper mix design and testing: slump flow > 600 mm; remain flowable ≥ 90 minutes; withstand a slope of 3%; pumpable ≥ 90 minutes through pipes ≥ 100 m long.

Recently, Wang and Shah et al. (2005, 2010) have developed a semi-flowable SCC (SFSCC) for slip form pavements. This SFSCC possesses not only the sufficient flow ability for self-consolidation but also sufficient strength to hold the shape of the concrete after paving. Through tailoring concrete materials and mix proportions, such SFSCC is designed to have the maximum self-consolidating ability with minimum flow ability. It can be used for slip form paving without additional consolidation. Two field applications (i.e., concrete deck and pavement construction) have been conducted using SFSCC in pavements with normal pavement cross slopes. The results indicate that well designed and well constructed SFSCC has performed satisfactorily in service.

Wang and Shah et al. (2005, 2010) found shape stability is a key factor for creating cross slopes. It can be obtained by rationally using various admixtures/additives, such as rheology and viscosity modifying admixtures and clays. The green strength, which is the strength of concrete at the plastic state, is associated with the friction and cohesion among the cement-coated aggregate particles. Concrete having higher green strength may have better the shape stability, but concrete shape stability combats with its flow ability. In order to achieve a proper SFSCC, a minimum shape stability or green strength of the concrete shall be obtained while sufficient flow ability is maintained for self-consolidation. Consequently, it is essential to find out the minimum green strength required for the concrete shape stability and the factors that affect concrete green strength.

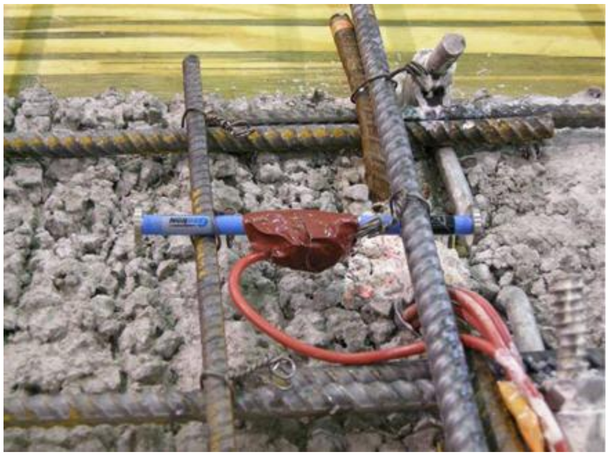
Surface Finish

The workability properties of SCC result in a much-improved surface finish over CVC. Since the motion of SCC under placement could be either a creeping movement or a rapid flow, the smooth surface finish between the concrete and the form can be achieved. The smooth finish minimizes for time-consuming cosmetic repairs and creates structural or architectural finishes which are not achievable with conventional concrete.

Because SCC surface replicates form imperfections, seam lines, and joint quite well, form and mold cleaning is a very critical task. Proper application of form release agents and tighter form tolerances should be implemented to avoid the accumulation of excessive form oil and the potential problems of discoloration and visible pour lines. Guidelines regarding selection of proper form oils that provide acceptable release properties, surface finishes, and form cleaning techniques are paramount to maintain forms in a manner that will result in high-quality finishes on concrete members made with SCC (PCI SCC, 04).

Wood and steel are the most popular material for producing forms. Ramsburg P. (2010) found the wood form induces fewer flaws than the steel form since wood forms soak up excess release agent. However, any small amount of extra oil on a steel form will react with the concrete mix and create small pinholes. Consequently, a clean and smooth surface is more essential for steel forms which need more attention to ensure the quality of surface. Ramsburg P. (2010) also investigated the barrier release agent and reactive release agent on the final appearance of the SCC product. The barrier release agent consistently produced a poor finish, even when more labor than usual was put into than the reactive release agent.

Shear transfer at construction joints and interfaces with other components is a concern in SCC due to smoothness of the surface and difficulty of roughing fresh concrete. Factors contributing to shear transfer are cohesion, interlock, and friction developed by the force in the reinforcement crossing the interface plane. Proper roughness of the interface between bridge deck and girder is very important to ensure adequate transfer shear and composite action.



(a) **Conventional Concrete** *(b)* **Self-Consolidating Concrete**

Figure 2: Surface of the top flange of a bridge girder (Boehm, 2008).

Boehm (2008) observed a separation and horizontal displacement, or "slip" of the cast-in-place (CIP) deck relative to the SCC girders in the flexural tests. This was attributed to inadequate surface roughening of the SCC girders compared to conventional concrete as shown in Figure 2. Both the AASHTO LRFD (2007) and ACI 318 specifications (2008) require at least one-quarter inch roughening to account for it in shear transfer calculations. This surface roughness is commonly achieved by raking the top surface of the girder top flange or using corrugated metal bulkhead at construction joint locations. However, surface roughening of SCC girders is difficult to achieve due to that fact that SCC simply re-consolidates following raking. In order to achieve proper surface roughness for composite members with a cast-in-place deck, raking of the SCC surfaces should be postponed until the initial setting begins, and the finished surface should be inspected carefully; otherwise, the use of shear keys should be considered.

Summary

Based on the literature survey presented in this paper regarding the formwork pressure, pumpability, cross slope, and surface finish of cast-in-place SCC, it is summarized as follows:

(1) To be safe, it is best to calculate form pressure through full liquid head. When designing form pressure via the method of ACI 347 (2004), the vertical height of liquid concrete in the forms should be determined. In order to design formwork and tie spacing for SCC for less than full liquid head, sensors can be used to get more accurate information. The factors affecting the formwork pressure have also been surveyed in the literature;

(2) Pumping differences exist between SCC and CVC. Proper sizing of lines and equipment can optimize the pumping operation. Three main causes of pump line blockage are mix design, problems with pipe network and operator error.

(3) In order to create cross slope for pavement and bridge construction, a modified SCC shall be used, such as SFSCC. The shape stability is a key factor for creating cross slopes and can be obtained by using various admixtures/additives. For example, SFSCC possesses not only the sufficient flow ability for self-consolidation but also sufficient strength to hold the shape of the concrete after paving.

(4) The smooth finish minimizes for time-consuming cosmetic repairs and creates structural or architectural finishes which are not achievable with conventional concrete. High-quality surface finish on concrete members made with SCC could be achieved by clean forms without significant flaws, proper application of

form release agents and tighter form tolerances. Surface roughening of SCC girders is difficult to achieve due to that fact that SCC simply re-consolidates following raking. Raking of the SCC surfaces should be postponed until the initial setting begins, and the finished surface should be inspected carefully; otherwise, the use of shear keys should be considered.

References

American Association of State Highway and Transportation Officials (AASHTO) (2007). *AASHTO LRFD Bridge Design Specifications: Customary U.S. Units (4th ed.),* Washington D.C.

American Concrete Institute (ACI). (2008). *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary (ACI 318R-08),* Farmington Hills, Michigan.

ACI Committee 237. (ACI 237) (2007). *Self-Consolidating Concrete.* American Concrete Institute (ACI).

ACI Committee 347. (ACI 347) (2004). *ACI 347-04: Guide to Formwork for Concrete.*

Assaad J. & Khayat K.H. (2005). Formwork pressure of self-consolidating concrete made with various binder types and contents. *ACI Materials Journal, 102*(4), 215-22.

Barragan B., Gettu R., Pintado X., & Bravo M. (2006). Design of high strength self-compacting concrete for tunnel linings. *Measuring, Monitoring and Modeling Concrete Properties, Part 5*, 485-491.

Boehm K.M. (2008). *Structural Performance of Self-Consolidating Concrete in AASHTO Type I Presstressed Girders*. M.S. thesis, Auburn University.

Freys D., Schutter G.D., Verhoeven R., & Khayat K.H. (2010). Similarities and Differences of Pumping Conventional and Self-Compacting Concrete. *Design, Production and Placement of Self-Consolidating Concrete*, Dordrecht, pp. 153-162.

Freys D., Verhoeven R., & Schutter G.D. (2009) Full scale pumping tests on SCC: application of the modified Hattori-Izumi theory. *3rd North American conference on the Design and Use of Self-Consolidating Concrete: Challenges and barriers to application: proceedings of SCC 2008*, Chicago, IL, USA, pp. 637-649.

Gregori A., Ferrpm R.P., Sun Z., & Shah S.P. (2008). Experimental Simulation of Self-Consolidating Concrete Formwork Pressure. *ACI Materials Mournal, 05*(1), 97-104.

Hodgson D., Schindler A.K., Brown D.A., & Mary S. (2005). Self-consolidating concrete for use in drilled shaft applications. *Journal of Materials in Civil Engineering*, *17*(3), 363-369.

Kahn L.F. and Kurtis. K.E. (2010). Concrete in congested sections: Mixture characteristics and assessment of performance. *PCI JOURNAL*, Winter, pp. 79-96.

Khayat K.H. & Mitchell D. (2009). Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements. *NCHRP Report 628 to National Cooperative Highway Research Program,* Transportation Research Board, Washinton, *D.C.*

Khrapko M. (2007). “Self Compacting Concrete – a Solution for Technology Hungry Concrete Construction”, CBE Consultancy Ltd.

Nasvik, J. (2004, Oct.). Formwork for Self-Consolidating Concrete: there are many good reasons to use SCC—but some cautions are necessary. *Concrete Construction*. [WWW document]. URL http://findarticles.com/p/articles/mi_m0NSX/is_10_49/ai_n6257803/.

Nowak A., Morcous G., & Tuan C.Y. (2007). Development of a Guide for Cast-in-Place Applications of Self-consolidating Concrete. *Technical Report SPR-l(07) 594 to Nebraska Department of Roads*, Department of Civil Engineering, University of Nebraska Lincoln, Lincoln, Nebraska.

Okamura, H., and Ouchi, M. (2003). Self-Compacting Concrete. *Journal of Concrete Technology*, 1(1), 5-15.

Ouchi M., Nakamura S. Osterberg T., Hallberg S., & Lwin M. (2003). Applications of Self-Compacting Concrete in Japan, Europe and the United States. *ISHPC*, pp. 1-20.

Precast/Prestressed Concrete Institute Interim SCC Guidelines FAST Team. (PCI SCC) (2003). Interim Guidelines for the Use of Self-Consolidating Concrete in Precast/Prestressed Concrete Institute Member Plants, fourth edition. *Precast/Prestressed Concrete Institute*, Chicago, IL.

Ramsburg P. (2010). Self Consolidating Concrete and Bug Holes. [WWW document]. URL http://www.todaysconcretetechnology.com/self-consolidating-concrete-and-bug-holes.html.

Wallevik J.E. (2003). Rheology of particle suspensions, fresh concrete, mortar and cement paste with various types of lignosulfonates. *Ph.D. Thesis*, NTNU, Trondheim.

Wang K., Shah S.P. & et al. (2005). Self-Consolidating Concrete—Applications for Slip-Form Paving:Phase I (Feasibility Study). *Technical Report, No. TPF-5(098) to Federal Highway Administration Transportation*, Center for Portlant Cement Concrete Pavement Technology, Iowa State University, Iowa.

Wang K., Shah S.P., Voigt T., & Mbele J.J. (2010). Using Fly Ash, Clay, and Fibers for Simultaneous Improvement of Concrete Green Strength and Consolidatability for Slip-Form Pavement. *Journal of Materials in Civil Engineering, 22*(2), 196-206.