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Self-Consolidating Concrete

Reported by ACI Committee 237



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Self-Consolidating Concrete

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Self-consolidating concrete (SCC) has been successfully used in many projects around the world and has made a major impact on concrete placement and construction economics. This report contains the current state of knowledge with respect to SCC. The information in this document is expected to inform concrete producers, users, and specifiers of SCC of known practices and processes. Because SCC is a viable solution to various concrete placement problems, ASTM has established Subcommittee C09.47, Self-Consolidating Concrete, to develop standard test methods for SCC.

Keywords: admixture; aggregate; air entrainment; bleeding; cement; consolidation; curing; placing; self-consolidating concrete; specification; viscosity, workability.

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Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

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CHAPTER 1—INTRODUCTION

1.1—Definition of self-consolidating concrete (SCC)

Self-consolidating concrete (SCC) is highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation. In general, SCC is concrete made with conventional concrete materials and, in some cases, with a viscosity-modifying admixture (VMA). SCC has also been described as self-compacting concrete, self-placing concrete, and self-leveling concrete, which all are subsets of SCC. The nomenclature of this technology has been previously discussed (Szecsy 2002). In this report, conventional concrete is referred to as concrete that does not meet the definition of SCC.

1.2—Advantages

Properly proportioned and placed SCC can result in both economic and technological benefits for the end user. The in-place cost savings, performance enhancements, or both, are the driving forces behind the use of SCC. Specifically, SCC can provide the following benefits:

- Reduce labor and equipment.
 - No need for vibration to ensure proper consolidation. This also results in savings in equipment purchasing and equipment maintenance and operation; and
 - Less need for screeding operations to ensure flat surfaces (self-leveling characteristic).
- Enable the casting of concrete that develops the desired

mechanical properties independent of the skill of the vibrating crew;

- Accelerate construction through higher rate of casting or placing and shorter construction duration;
- Facilitate and expedite the filling of highly reinforced sections and complex formwork while ensuring good construction quality. This can ensure better productivity, reduce the labor requirement and cost, or both;
- Enable more flexibility in spreading placing points during casting. This can reduce the need for frequent movement of transit trucks and the need to move the pump lines to place concrete (possible reduction in the number of pumps, pump operators, and so on). This greater flexibility in scheduling construction activities and procuring the required resources results in both time and resource savings;
- Reduce noise on the job site (especially critical in urban areas and for sections requiring heavy vibration consolidation):
 - Reduce the need of vibration for construction typically requiring the use of heavy consolidation (such as fiber-reinforced concrete and precast operations). In some cases, the use of noise-free or silent concrete can potentially extend construction hours in urban areas, enabling the scheduling of some construction activities during otherwise curfew periods to alleviate difficulties related to traffic conditions in urban areas; and
 - Reduce insurance premiums. Precasting facilities generating considerable noise pollution are sometimes required to pay premiums to national insurance agencies responsible for eventual treatment of hearing-impaired workers. Insurance premium reductions can partially offset the additional material cost of SCC, making it attractive for precast operations.
- Decrease employee injuries by facilitating a safer working environment where strenuous and labor-intensive operations can reduce tripping hazards through the removal of some electrical cords or air lines (Walraven 2003);
- Permit more flexibility for detailing reinforcing bars. Avoid the need to bundle reinforcement to facilitate placement and consolidation, and in some cases, enable the use of small and closely spaced reinforcing steel to control cracking;
- Create smooth surfaces free of honeycombing and signs of bleeding and discoloration, obtained when using a well-proportioned SCC mixture, high-quality formwork with an adequate release agent, and sound placement practices (Chapter 6). Superior surface quality is critical in architectural concrete and cast-in-place and precast concrete for residential construction (walls); and
- Eliminate the need for materials, such as underlayments, that are used to level and prepare substrates for final flooring materials, such as carpeting and tile, whenever allowed by building regulations.

1.3—Development history of SCC

The use of SCC has gained wide acceptance in Japan since the late 1980s. Initially, it was developed to ensure proper consolidation in applications where concrete durability and service life were of concern. SCC was later used to facilitate construction operations and reduce construction time and cost. For example, it has been used to cast sections with highly congested reinforcement and areas that present restricted access to placement and consolidation, including the construction of tunnel lining sections and the casting of hybrid concrete-filled steel tubular columns. The following references provide various examples of the early use of SCC in civil engineering applications: Tanaka et al. (1993); Hayakawa et al. (1993, 1995); Miura et al. (1993); Okamura and Ozawa (1994); Takeuchi et al. (1994); Izumi et al. (1995); Fukute et al. (1995); Kitamura et al. (1996); and Ushijima et al. (1995).

SCC has recently been used in concrete repair applications in Canada and Switzerland, including the repair of bridge abutments and pier caps, tunnel sections, parking garages, and retaining walls, where it ensured adequate filling of restricted areas and provided high surface quality (Jacobs and Hunkeler 2001; Khayat and Morin 2002).

Since the early development of SCC in Japan, this new class of high-performance concrete has been employed in several countries in cast-in-place and precast applications (RILEM 2000; Khayat and Aïtcin 1998; Skarendahl 2001; Walraven 2001; Ouchi 2001).

The use of SCC in North America has grown dramatically, especially in the precast industry, where it has been used in regular production at precast plants in the United States since 2000. The majority of such concrete has been used to produce precast elements for parking garage structures and architectural panels. The estimated volume of SCC in the precast market in the United States was 177,000 yd³

Table 1.1—SCC project video clips*

Project type	Residential footings*	Precast jail cell*	Prestress double-tee*	Wall panel*	Wall panel*
Slump flow, in. (mm)	26 (650)	28 (700)	23 (575)	26 (650)	N/A
Slump, in. (mm)	N/A	N/A	N/A	N/A	8 (200)

*Click blue link of a table column heading to view related video.

(135,000 m³) in 2000; it increased to 2.3 million yd³ (1.8 million m³) in 2003. * In 2002, 40% of precast manufacturers in the United States had used SCC, and in some cases, new plants are currently being built around the idea of using SCC technology. * On the other hand, the use of SCC in the ready mixed concrete industry is still in its infancy in the United States, with estimated production in 2002 limited to 130,000 yd³ (100,000 m³) (Vachon and Daczko 2002).

1.4 — Selected case studies

Table 1.1 includes video clips of several SCC applications. For comparison purposes, there are clips showing a precast wall panel being produced with both conventional 8 in. (200 mm) slump concrete and SCC. Following Table 1.1 are five case studies that describe projects where SCC has been successfully used in North America. The mixture proportions included in these case studies are for example purposes only. For development of SCC mixture proportions, guidelines are provided in [Chapter 4](#).

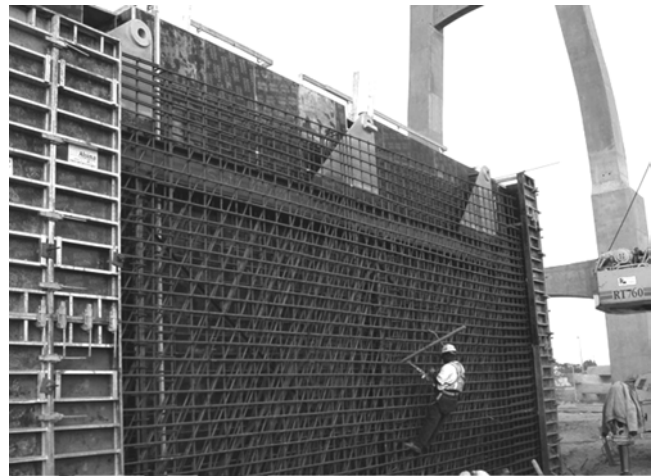
*Daczko, J., 2003, "Use of SCC in the Precast Industry in the United States." (private communication)

Pedestrian Overpass (I-4), Seminole County, Orlando, Fla.

Challenge: The required mixture was to be placed within an anchor block structure as part of the pedestrian overpass. The 3 in. (75 mm) maximum slump for the Class IV FL DOT concrete mixture, combined with two channel sections that ran the length of the sides toward the top of the block, made it virtually impossible to use an immersion vibrator for proper consolidation of the concrete.

Solution: The contractor proposed using SCC to properly fill and consolidate the concrete for this reinforced concrete structure. The only change to the specification was the elimination of the slump requirement to allow the use of SCC.

To view related video, [click here](#).



Mixture proportions:

Cement:	530 lb/yd ³ (309 kg/m ³)
GGBFS/fly ash:	120 lb/yd ³ (77 kg/m ³)
Coarse aggregate (No. 57):	1152 lb/yd ³ (684 kg/m ³)
(No. 89):	542 lb/yd ³ (322 kg/m ³)
Fine aggregate:	1277 lb/yd ³ (758 kg/m ³)
w/cm:	0.43

Admixtures:

HRWRA:	15 fl oz/cwt (9.8 mL/kg)
WRA:	1.5 fl oz/cwt (1.0 mL/kg)
VMA:	3.0 fl oz/cwt (1.95 mL/kg)

Fresh concrete properties:

Slump flow: 28 in. (710 mm)

Compressive strength:

24 hours: 1800 psi (12.4 MPa)
 30 hours: 2500 psi (17.2 MPa)
 28 days: 7460 psi (51.5 MPa)

Engineer/Architect/Specifier: Harding ESE (a Mactec Company)

Concrete producer: RMC Ewell

Contractor: Martin K. Eby Construction Co., Inc.

Comments:

- ~ Haul time was approximately 30 to 45 minutes.
- ~ 22 ft (6.7 m) high walls, 58 ft (17.7 m) long.
- ~ Engineered cold joint at 11 ft (3.4 m).
- ~ SCC allowed to free fall 15 ft (4.6 m).
- ~ No mechanical vibration.
- ~ During one delay in placement, the mixture maintained its workability for 2.5 hours at 90 °F (32 °C).
- ~ Excellent aesthetics.

National Museum of the American Indian, Washington, D.C.

The National Museum of the American Indian (NMAI) was built on the Washington Mall and is intended to resemble a solid piece of rock carved over time by wind and water. Everything is highly symbolic and nonrepetitive. The five-story building has an area of approximately 260,000 ft² (24,000 m²). The entire structure has no right angle, and the forms were all custom built.

The main reason to use an SCC mixture was the overcrowded reinforcement and the complicated shapes of the structure. There was little to no room left for vibrators. Vibration caused forms to fail in certain instances. A significant amount of the concrete was exposed. SCC enabled the placing of certain elements in one lift and significantly improved the aesthetics. The stress on the formwork was also reduced due to the use of SCC, as the vibration could be eliminated. The use of SCC also enabled turnaround times to be reduced from 5 days to 2 days.

The total quantity of SCC used was greater than 30,000 yd³ (23,000 m³).


Mixture proportions:

Cement (Type 1):	390 lb/yd ³ (230 kg/m ³)
GGBFS:	260 lb/yd ³ (155 kg/m ³)
Coarse aggregate:	Gravel (No. 67)
w/cm:	0.47

Admixtures:

HRWRA:	8 fl oz/cwt (5.2 mL/kg)
--------	-------------------------

Fresh concrete properties:

Air content:	6.0%
Slump flow:	24 in. (610 mm)
Unit weight:	148 lb/ft ³ (2370 kg/m ³)

Compressive strength:

28 days: 6000 psi (41.4 MPa)

Owner: Smithsonian Institution

Concrete producer: Aggregate Industries, Maryland

General contractor: Joint venture between Clark Construction Group Inc. and Table Mountain Rancheria Enterprises (TMR) of Faint, Calif., an American Indian firm.

Double-Tee Production, Nitterhouse Concrete Products Inc., Chambersburg, Pa.																											
Nitterhouse is a producer of double tees for precast parking garages, and it is involved throughout the construction process from specifications to erection. Nitterhouse places one 500 ft (150 m) bed and one 380 ft (115) bed of double tees on a daily basis. The particular project is the parking garage at Harrisburg International Airport, Harrisburg, Pa. All-white cement was used in this project to increase the reflectivity of the structure without the need for paint.																											
The main reason for the use of SCC was cost savings, arising from the reduction in labor costs. Other benefits for the use of SCC included improved appearance of the concrete and reduction in noise levels.																											
Mixture proportions: <table><tr><td>Cement (Type I):</td><td>639 lb/yd³ (385 kg/m³)</td></tr><tr><td>GGBFS:</td><td>113 lb/yd³ (68 kg/m³)</td></tr><tr><td>Coarse aggregate:</td><td>Gravel (No. 57)</td></tr><tr><td>w/cm:</td><td>0.40</td></tr></table> Admixtures: <table><tr><td>HRWRA:</td><td>9 fl oz/cwt (5.9 mL/kg)</td></tr><tr><td>Set accelerator:</td><td>12 fl oz/cwt (7.85 mL/kg)</td></tr><tr><td>VMA:</td><td>4 gal./yd³ (20 L/m³)</td></tr></table>		Cement (Type I):	639 lb/yd ³ (385 kg/m ³)	GGBFS:	113 lb/yd ³ (68 kg/m ³)	Coarse aggregate:	Gravel (No. 57)	w/cm:	0.40	HRWRA:	9 fl oz/cwt (5.9 mL/kg)	Set accelerator:	12 fl oz/cwt (7.85 mL/kg)	VMA:	4 gal./yd ³ (20 L/m ³)	Fresh concrete properties: <table><tr><td>Air content:</td><td>5.5%</td></tr><tr><td>Slump flow:</td><td>22 ± 2 in. (560 ± 50 mm)</td></tr><tr><td>Unit weight:</td><td>148 lb/ft³ (2370 kg/m³)</td></tr></table> Compressive strength: <table><tr><td>13 hours:</td><td>4000 psi (27.6 MPa)</td></tr><tr><td>28 days:</td><td>>7200 psi (>49.7 MPa)</td></tr></table>		Air content:	5.5%	Slump flow:	22 ± 2 in. (560 ± 50 mm)	Unit weight:	148 lb/ft ³ (2370 kg/m ³)	13 hours:	4000 psi (27.6 MPa)	28 days:	>7200 psi (>49.7 MPa)
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Concrete producer: Nitterhouse Concrete Products Inc., Chambersburg, Pa.																											

Rosenthal Center for Contemporary Arts, Cincinnati, Ohio

Challenge:

1. One component of the design of this building was a roll-up that resembled a 96 ft (29.3 m) 3/4 circular section that connected the wall to the floor. The form for this curved roll-up provided very little access for internal vibration; and

2. Formwork for structural diamond-shaped columns consisted of square column forms with plywood inserts to create their diamond shape. The form detail resulted in “dead areas” on two sides that restricted access for proper vibration of the concrete.

Solution:

To ensure proper consolidation and to minimize surface blemishes, SCC using a a blend of aggregates was selected for both the roll-up section and the diamond-shaped columns.

**Mixture proportions:**

Cement (Type I):	750 lb/yd ³ (445 kg/m ³)
Coarse aggregate (No. 57):	1000 lb/yd ³ (593 kg/m ³)
(No. 8):	500 lb/yd ³ (297 kg/m ³)
Fine aggregate:	1500 lb/yd ³ (890 kg/m ³)
Water:	300 lb/yd ³ (178 kg/m ³)
w/cm:	0.40

Admixtures:

HRWRA:	12.0 fl oz/cwt (7.8 mL/kg)
VMA:	1.5 fl oz/cwt (1.0 mL/kg)

Fresh concrete properties:

Slump flow: 26 in. (660 mm)

Compressive strength:

Requirement

3000 psi (21 MPa) at 3 days
6000 psi (42 MPa) at 28 days

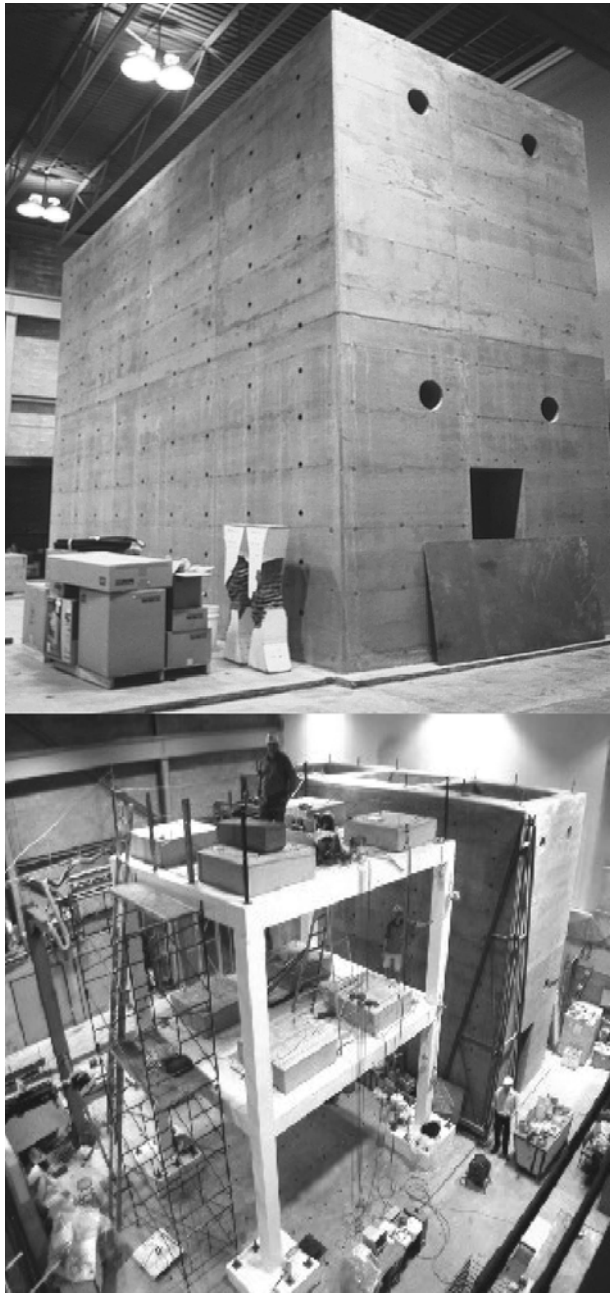
Actual

6600 psi (45.5 MPa) at 3 days
9000 psi (62.1 MPa) at 28 days

Engineer/Architect/Specifier: Zaha Hadid
Concrete producer: Hilltop Basic Resources
Contractor: Baker Concrete Construction

Comments:

- ~ The surface appearance of both the roll-up and column significantly enhanced over that of a conventional concrete mixture.
- ~ For the first two columns, an increase of approximately 20% in concrete volume placed per man-hour was achieved compared with the placement rate for a conventional 8 in. (200 mm) slump concrete. As construction progressed, the placement efficiency increased in excess of 350% of the conventional mixture.
- ~ There was increased job-site safety because vibration was eliminated; there was decreased tripping over power cords and decreased electrocution potential.

Reaction Wall in Structural Laboratory, Université de Sherbrooke, Sherbrooke, Quebec, Canada																													
A strong reaction wall design to enable dynamic testing of large structural sections was constructed at the structural engineering laboratory at the Université de Sherbrooke using high-performance SCC. This project started in late 1997 and targeted demonstrating the use of SCC in structural applications. The wall measures 30.5 ft (9.3 m) wide, 23 ft (7 m) high, and 13 ft (4 m) thick, and has three hollow sections in the middle. The wall is supported on a 9.8 ft (3 m) deep foundation system made of a series of highly reinforced beams anchored to rock bed. The wall is moderately reinforced with reinforcement steel and post-tensioning rods. The total volume of the SCC used to build the wall was 315 yd³ (240 m³), with 105 yd³ (80 m³) used for the underground section and 78 yd³ (60 m³) for each of the two 10.5 ft (3.5 m) high lifts above ground level. Concrete was produced in a local concrete plant and was delivered in batches of 7.8 yd³ (6 m³). In total, 40 concrete deliveries were tested upon arrival at the job site. The SCC was pumped into place and spread readily among the reinforcement. SCC enabled the placing of the concrete from two points along the wall. The use of SCC reduced the noise in the laboratory and facilitated construction activities in a working environment. High quality was secured.																													
Mixture proportions: <table><tr><td>Cements:</td><td>880 lb/yd³ (520 kg/m³)</td></tr><tr><td>Mass of fine aggregates:</td><td>Crushed aggregate (5 to 10 mm)</td></tr><tr><td>w/cm:</td><td>0.42</td></tr></table> Admixtures: <table><tr><td>HRWRA:</td><td>4.4 fl oz/cwt (2.9 mL/kg)</td></tr><tr><td>Liquid-based VMA:</td><td>9.2 fl oz/cwt (6.0 mL/kg)</td></tr><tr><td>WRA:</td><td>2 fl oz/cwt (1.3 mL/kg)</td></tr></table>		Cements:	880 lb/yd ³ (520 kg/m ³)	Mass of fine aggregates:	Crushed aggregate (5 to 10 mm)	w/cm:	0.42	HRWRA:	4.4 fl oz/cwt (2.9 mL/kg)	Liquid-based VMA:	9.2 fl oz/cwt (6.0 mL/kg)	WRA:	2 fl oz/cwt (1.3 mL/kg)	Fresh concrete properties: <table><tr><td>Air content:</td><td>1.0%</td></tr><tr><td>Slump flow:</td><td>25 in. (640 mm); COV* = 3%</td></tr><tr><td>V-funnel flow time:</td><td>3.8 seconds; COV = 24%</td></tr><tr><td>Caisson filling capacity:</td><td>83%; COV = 5%</td></tr></table> Compressive strength: <table><tr><td>24 hours:</td><td>870 psi (6 MPa); COV = 22%</td></tr><tr><td>7 days:</td><td>3700 psi (25.5 MPa); COV = 12%</td></tr><tr><td>28 days:</td><td>6100 psi (42 MPa); COV = 6%</td></tr></table> *COV = coefficient of variation, determined from testing performance of 40 concrete deliveries.		Air content:	1.0%	Slump flow:	25 in. (640 mm); COV* = 3%	V-funnel flow time:	3.8 seconds; COV = 24%	Caisson filling capacity:	83%; COV = 5%	24 hours:	870 psi (6 MPa); COV = 22%	7 days:	3700 psi (25.5 MPa); COV = 12%	28 days:	6100 psi (42 MPa); COV = 6%
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Owner: Université de Sherbrooke Concrete producer: Demix béton, Sherbrooke																													

CHAPTER 2—FRESH PROPERTIES

2.1—Terminology relative to SCC

SCC is highly flowable, nonsegregating concrete that can spread into place, fill formwork, and encapsulate reinforcement without any mechanical consolidation. SCC rheology is characterized by a low yield stress to ensure high deformability and moderate plastic viscosity to maintain homogeneous suspension of solids, hence reducing interparticle collision, segregation, and flow blockage. The main requirements of SCC involve securing high levels of deformability while maintaining a highly stable mixture. These characteristics are further elaborated on and defined as follows.

Rheology refers to the science of deformation, and flow of matter is fundamental to understanding the flow of fresh SCC. Concrete rheology is evaluated using special rheometers that enable one to relate variations in shear stress to shear rate. SCC is sometimes described as a Bingham fluid in which the shear stress can be expressed as

$$\tau = \tau_0 + \mu_p \cdot \gamma$$

where τ is the shear stress (Pa); τ_0 is the yield stress (Pa); μ_p is the plastic viscosity (Pa·s); and γ is the shear rate. The **yield stress** corresponds to the minimum shear stress required to initiate flow. Below such value, the mixture does not undergo any deformation and, therefore, does not flow. The constant of proportionality between shear stress and shear rate is referred to as the plastic viscosity and refers to the resistance of the plastic material to undergo a given flow. A video clip of both a low and high viscosity SCC mixtures is included in [Table 2.1](#).

Workability describes the ease with which concrete can be mixed, placed, consolidated, and finished. Workability of SCC is described in terms of filling ability, passing ability, and stability, and is characterized by specific testing methods.

The **filling ability** (unconfined flowability) describes the ability of SCC to flow into and fill completely all spaces within the formwork, under its own weight. This property is of importance when selecting the casting technique and determining spacing between filling points.

The **passing ability** (confined flowability) refers to the ease with which concrete can pass among various obstacles and narrow spacing in the formwork without blockage. Blockage refers to the condition that can arise from local aggregate segregation in the vicinity of the obstacles that give rise to interlocking and blockage of the flow in the absence of any mechanical vibration. SCC can exhibit high **filling capacity** if it can achieve the levels of both filling ability and passing ability required to readily fill a predetermined section under the sole action of gravity.

Stability of concrete describes the ability of a material to maintain homogeneous distribution of its various constituents during its flow and setting. There are two types of stability characteristics that are important for SCC: dynamic and static stability.

Dynamic stability refers to the resistance of concrete to the separation of constituents during placement into the formwork. Adequate dynamic stability is required for SCC

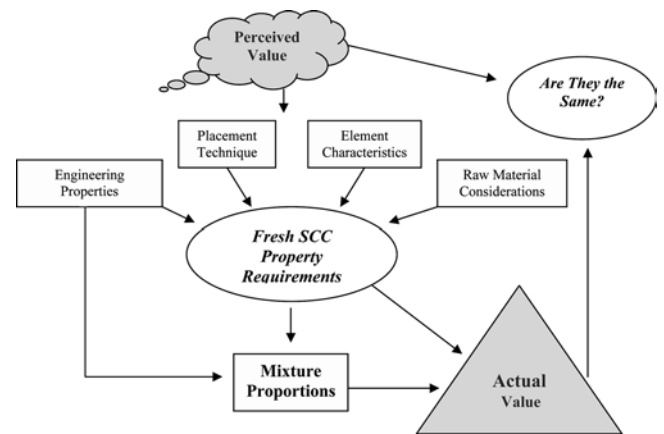


Fig. 2.1—Variables involved in establishing the required fresh SCC properties.

when the application has requirements such as flowing through closely spaced obstacles and narrow spaces. It is also important if the SCC will be transported without agitation.

Static stability refers to the resistance of concrete to bleeding, segregation, and surface settlement after casting while the concrete is still in a plastic state.

In some cases, VMAs or higher powder contents will be used to promote stability. A VMA is an admixture used for enhancing the rheological properties of cement-based materials in the plastic state to reduce the risk of segregation and washout.

2.2—Performance requirements of SCC

In general, the performance requirements of SCC are complex and depend on several parameters, including service loading and environmental conditions, intended placement method, labor skill, and quality assurance and quality control measures.

The required workability for **placing** concrete depends on the type of construction, selected placement and consolidation methods, complexity of the formwork, and structural design details that affect the degree of congestion of the reinforcement.

Figure 2.1 shows the many variables that influence the desired fresh properties of SCC (Khayat and Daczko 2002). Not only are project and raw material variables accounted for, but economic variables should also be considered. As shown in Fig. 2.1, an initial perceived value drives the user to try SCC; however, the real question is, “is the actual value, which is determined after evaluation, equivalent to the initial perceived value?” This is where the mixture qualification process becomes important, and by committing oneself to the time required to investigate these variables, the most cost-effective solution will be determined.

2.3—General

It is the fresh, plastic properties of SCC that differentiate the material from conventional concrete.

In outlining and defining the fresh properties, two points of view can be used. The first is in defining the fundamental rheological properties of the SCC mixture. The