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Development of high-strength, economical self-consolidating concrete

Tarun R. Naik [a,*], Rakesh Kumar [a,1], Bruce W. Ramme [b], Fethullah Canpolat [c]

[a] UWM Center for By-Products Utilization, Department of Civil Engineering and Mechanics, University of Wisconsin–Milwaukee, P.O. Box 784, Milwaukee, WI 53201, United States
[b] Environmental, We Energies, 333 West Everett Street, Milwaukee, WI 53203, United States
[c] Yildiz Technical University, Civil Engineering Faculty, Department of Civil Engineering, Davutpasa Campus, Esenler, Istanbul 34220, Turkey

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ABSTRACT

This paper presents information regarding development, properties, and advantages and disadvantages of using high-strength self-consolidating concrete in the construction industry. It also presents results of a study recently completed for manufacturing economical high-strength self-consolidating concrete containing high-volumes of fly ash. In this study, portland cement was replaced by Class C fly ash in the range of 35–55% by the mass of cement. The results of fresh and hardened properties of concrete show that the use of high-volumes of Class C fly ash in self-consolidating concrete reduces the requirements for superplasticizer (HRWRA) and viscosity modifying agent (VMA) compared with the normal dosage for such admixtures in self-consolidating concrete. The results further indicate that economical self-consolidating concrete with 28-day strengths up to 62 MPa can be made using high-volumes of fly ash. Such concretes can be used for a wide range of applications from cast-in-place to precast concrete construction.

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1. Introduction

Technologies change perceptions. In the last two decades, concrete has no longer remained a material just consisting of cement, aggregates, and water, but it has become an engineered custom-tailored material with several new constituents to meet many varied requirements of the construction industry. Self-consolidating concrete, a recent innovation in concrete technology is being regarded as one of the most promising developments in the construction industry due to numerous advantages of it over conventional concrete. Self-consolidating concrete, as the name indicates, is a type of concrete that does not require external or internal compaction, but it becomes leveled and compacted under its self-weight only. It is commonly abbreviated as SCC and defined as a concrete which can be placed and compacted into every corner of a form work, purely by means of its self-weight thus eliminating the need of vibration or other types of compacting effort [1]. Self-consolidating concrete was originally developed at the University of Tokyo, Japan, in collaboration with leading concrete contractors during the late 1980s. The notion behind developing this concrete was concerns regarding the homogeneity and compaction of cast-in-place concrete within intricate (i.e., highly reinforced) structural elements, and to improve overall durability of concrete [2]. SCC is highly flowable and yet cohesive enough to be handled without segregation. It is also referred as self-compacting concrete, self-leveling concrete, super-workable concrete, highly-flowable concrete, non-vibrating concrete, etc. [3].

Hoshimoto et al. [4] visualized and explained the blocking mechanism of heavily reinforced section during placement of concrete and reported that the blockage of the flow of concrete at a narrow cross-section occurs due to the contact between coarse aggregate particles in concrete. When concrete flows between reinforcing bars, the relative locations of coarse aggregate particles are changed. This develops shear stress in the paste between the coarse aggregate particles, in addition to compressive stress. For concrete to flow through such obstacles smoothly, the shear stress should be small enough to allow the relative displacement of the aggregate. To prevent the blockage of the flow of concrete due to the contact between coarse aggregate particles, a moderate viscosity of the paste is necessary. The shear force required for the relative displacement largely depends on the water-to-cementitious materials ratio (W/Cm) of the paste. An increase of the water-to-cementitious materials ratio increases the flowability of the cement paste at the cost of decreases in its viscosity and deformability, as well as, of course, decrease in its mechanical and durability properties, which are the primary requirements for a structural-grade self-consolidating concrete. The self-consolidating concrete is flowable as well as deformable without segregation [1,3,5,6]. Therefore, in order to maintain deformability along with flowability in the paste, a superplasticizer is considered indispensable in such concretes to maintain a reduction in W/Cm. With a superplasticizer, the paste can be made more flowable with little concomitant decrease in viscosity [1]. An optimum

* Corresponding author. Tel.: +1 414 229 6696; fax: +1 414 229 6958.
E-mail address: tarun@uwm.edu (T.R. Naik).
[1] Formerly.

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combination of water-to-cementitious material ratio and superplasticizer for achievement of self-compactability can be derived for fixed aggregate content of the concrete through laboratory trial mixture proportioning. Okamura [1] has suggested a limiting value of coarse aggregate and fine aggregate for self-consolidating concrete at around 50% of the solid volume for the concrete for coarse aggregates and 40% for the mortar for fine aggregates.

Mehta [7] and Neville [8] have suggested a simple approach of increasing the sand content and reducing coarse aggregate content by 4–5% to avoid segregation. High flowability requirement of self-consolidating concrete leads to the use of mineral admixtures such as coal fly ash in its manufacturing. Fly ash particles are spherical; leading to reduced friction during flow of the mortar fraction in the concrete. Use of mineral admixtures such as fly ash, blast furnace slag, limestone powder, and other similar fine powder additives, increases the fine materials in the concrete mixture [1]. Use of mineral admixtures also usually reduces the cost of concrete, especially in the USA and many other countries where coal fly ash is readily and abundantly available. The incorporation of one or more mineral additives or powder materials having different morphology and grain-size distribution can improve particle-packing density and reduce inter-particle friction and viscosity. Hence, it improves deformability, self-compactability, and stability of the self-consolidating concrete [9].

Yahia et al. [10] and Naik and Kumar [11] have reported a reduction in the dosages of superplasticizer by using mineral additives in self-consolidating concrete requiring similar slump-flow compared to concrete made with portland cement only. The well-known beneficial advantages of using fly ash in concrete [12] such as improved rheological properties and reduced cracking of concrete due to the reduced heat of hydration of concrete can also be incorporated in SCC by utilization of fly ash as a filler.

Fly ash was added to help increase fluidity of the concrete because fly ash particles are spherical and has been known to increase workability and cohesiveness [13,14].

SCC can incorporate several minerals and chemical admixtures, in particular a HRWRA and a VMA. The HRWRA is used to insure high-fluidity and to reduce the water-to-cementitious materials ratio. The VMA is incorporated to enhance the yield value, reduce bleeding and segregation, and increase the viscosity of the fluid mixture. The homogeneity and uniformity of the self-consolidating concrete is not affected by the skill of workers, or the shape and bar arrangement of the structural elements because of high-fluidity and segregation-resisting power of SCC [1].

A highly flowable concrete is not necessarily self-consolidating because self-consolidating concrete should not only flow under its own weight but also fill the entire form and achieve uniform compaction without segregation. Fibers are sometimes used in self-consolidating concrete to enhance its tensile strength and delay the onset of tension cracks due to heat of hydration resulting from high cement content in SCC [3]. Use of high-volume Class F fly ash in SCC is also reported [11,15] for the development of economical and environmentally friendly SCC.

2. Development of mixture proportioning for high-strength SCC

Self-consolidating concretes typically have a higher content of fine particles and improved flow properties compared to the conventional concrete. It has three essential properties when the concrete is fresh (i.e., just made): filling ability; resistance to segregation; and, passing ability. SCC consists of cement, fine and coarse aggregates, mineral and chemical admixtures, and water. Self-compactability of concrete can be affected by the physical characteristics of materials and mixture proportioning. The mixture proportioning is based upon creating a high-degree of flowability while maintaining a low (<0.40) W/Cm. This is achieved by using high-range water-reducing admixtures (HRWRA) combined with stabilizing agents such as VMA to ensure homogeneity of the mixture [2].

A number of methods exist to optimize the concrete mixture proportions for self-consolidating concrete. One of the optimization processes suggested by Campion and Jost [2] is:

1. W/Cm equal to regular plasticized concrete, assuming the same required strength.
2. Higher volume of fines (for example, cement, fly ash, and other mineral additives) than a regular plasticized concrete.
3. Optimized gradation of aggregates.
4. High-dosage of HRWR (0.5–2% by mass of cementitious materials [Cm], 460–1700 mL/100 kg of Cm, or 7–26 fl. oz/100 lbs of Cm).

Another method for mixture proportioning for self-consolidating concrete was suggested by Okamura [1]. In this method:

1. Coarse aggregate content is fixed at 50% of the solid volume.
2. Fine aggregate is placed at 40% of the mortar fraction volume.
3. Water-to-cementitious materials ratio by volume is selected at 0.9 to 1.0 depending on properties of the cementitious materials.
4. HRWRA dosage and the final W/Cm value are determined so as to ensure the self-compactability.

Several other mixture proportioning methods for SCC have also been reported [7,8,16]. However, a rational mixture proportioning method for self-consolidating concrete should also have a variety of finer materials, as necessary. Optimum mixture proportions are sensitive to small variations in the characteristics of the components, such as the type of sand and fillers (shape, surface, grading) and the moisture content of the sand. Therefore, SCC cannot simply be made on the basis of a recipe.

3. Evaluation of self-compactability of fresh concrete

A number of test methods such as slump-flow, U-flow, V-flow time, L-box, and J-ring tests are in use for the evaluation of self-consolidating properties of the concrete. These test methods have two main purposes. One is to judge whether the concrete is self-compactable or not, and the other is to evaluate the deformability or viscosity for estimating proper mixture proportioning if the concrete does not have sufficient self-compactability [17]. The most commonly used methods for this purpose are discussed briefly in the following sections.

3.1. Slump-flow test

Slump-flow testing is the simplest and most commonly adopted test method for evaluating the flowability quality of self-consolidating concrete (ASTM C 1611). An ordinary Abram's slump cone is filled with concrete without any tamping. The cone is lifted and the diameter of the concrete after the flow has stopped is measured (Fig. 1). The mean diameter in two perpendicular directions of the concrete spread is taken as the value of slump-flow. Self-consolidating concrete is characterized by a slump-flow of 650–700 mm (26–28 in.). Measurement of slump-flow indicates the flowability of self-consolidating concrete and determines the consistency and cohesiveness of the concrete [2]. The slump-flow test measures the capability of concrete to deform under its own weight against the friction on the surface of the base plate with no other external resistance present [9,18–20]. According to Nagataki and Fujiwara [21], a slump-flow ranging from 500 to 700 mm (20–28 in.) is