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Tensile strength and paste–aggregate bonding characteristics of self-consolidating concrete

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HIGHLIGHTS

- Slump flow and U-box tests showed that the SCC fresh concrete achieved good compactability, filling and self-consolidation.
- SCC exhibited higher strengths (tensile and compressive) than normal concrete even at earlier curing times (i.e., 7-day).
- SCC cut samples showed less air voids compared to normal concrete by 15 to 20 percent.
- Microstructural inspection showed that the bond cracks in the SCC's ITZ were smaller than the cracks in the normal concrete.
- The amount of fractured aggregate during tensile splitting test was greater for SCC than that of normal concrete by 15%.

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ABSTRACT

The main focus of this study was to assess and compare the tensile and compressive strengths of normal and self-consolidating concrete (SCC) through microstructural characteristics such as the interfacial transition zone (ITZ) and cracking patterns. These evaluations indicated that the ITZ bond cracks widths of SCC were smaller than those of the normal concrete, a fact that may have contributed to the increased strength of the SCC. It was also observed that splitting tensile fractures generally took place within the ITZ for normal concrete while they more frequently ran through the coarse aggregates in SCC, indicating a stronger ITZ of this type of concrete.

1. Introduction

The development of self-consolidating concrete (SCC) was associated with the drive towards better quality concrete pursued in Japan around 1983, where lack of uniform and complete compaction had been identified as the primary factor responsible for poor performance of concrete structures [1–4]. This was mainly related to a drop in the number of skilled construction workers leading to a similar trend in the quality of placed concrete and construction jobs in general [5–7]. For these reasons, SCC was designed to compact under its own mass in order to eliminate the problem of inadequate consolidation in thin sections or areas of congested reinforcement encountered in conventional or normal concrete [8–10]. As a result of the new and improved mix designs in recent years, SCC has started to be used in Japan and Europe more often in various bridge repair and rehabilitation applications [11,12]. In the United States, SCC has been cautiously used in last decade due to its high initial costs and limited knowledge and experience related to both design and placement.

Typically, poor compaction leads to large volumes of entrapped air voids in the hardened concrete and compromises the strength and durability of concrete [13–16]. Self-consolidating concrete is able to flow and consolidate under its own weight, without any external vibration, and little air is entrapped while flowing in the formwork [17,18]. At the same time, it is cohesive enough to fill spaces of almost any size and shape without segregation or bleeding [19,20] if properly designed. This makes SCC particularly useful wherever placing is difficult, such as in heavily-reinforced concrete members or in complicated work-forms [21,22]. With regard to its composition, self-consolidating concrete consists of the same basic components as conventionally vibrated concrete, which are cement, aggregates, and water, except for the chemical and mineral admixtures added in different proportions so that good self-com-

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pactability can be achieved. Generally, this is achieved through a relatively high fine aggregate to coarse aggregate proportion, a low water–cement ratio and proper amounts of chemical and mineral admixtures combined such that the concrete exhibits excellent workability and an increased resistance to segregation during placing.

Chemical admixtures are used to affect various concrete properties such as setting time, water demand, air entraining characteristics and workability. With respect to SCC, high-range water-reducing (HRWR) and viscosity-modifying admixtures (VMA) play the most important role allowing the concrete to flow more easily with cohesiveness, filling the formwork and encapsulating the reinforcing cage, while avoiding segregation and excessive bleeding. Typically, SCC contains mineral admixtures, also known as supplementary cementing materials (SCM) to increase the fines content without using excessive portland cement and to reduce costs. These cementitious materials are derived from various industrial operations and are used with a mass often equal to the mass of portland cement in the concrete mixture. The main types of mineral admixtures used to replace the portland cement in concrete mixes are fly ash, slag cement, and silica fume [23–27].

Although, SCC has many benefits such as less labor during mixing and placing, improved mechanical properties, increased durability, and reduced construction noise, there are also concerns associated with the use of some mineral admixtures (e.g., granulated slag and silica fume). Among these concerns are lower strengths, bleeding or segregation and shrinkage cracking [24,25]. The work conducted in this study tried to address some these concerns to further the existing work in this area.

2. Research methodology

The main objectives of this research were: (1) To evaluate two test methods typically used for fresh self-consolidating concrete – slump flow and U-tube; (2) To compare the splitting tensile strength and compressive strength of self-consolidating and normal concrete; (3) To examine the bonding between coarse aggregates and cement paste; and (4) To visualize the coarse aggregate distribution in both types of concrete specimens. The bonding between the cement paste and coarse aggregate was investigated by studying the interfacial transition zone (ITZ) of the two types of concrete under the scanning electron microscope (SEM). The ITZ is a narrow area surrounding the aggregate particles where the cement paste is mostly comprised of calcium hydroxide. This region is very porous due to a high water-cement ratio and tends to increase as the aggregate size increases. It is believed that this transition zone directly affects the concrete properties, especially its strength and stiffness, due to its weaker structure compared to the bulk paste in the concrete. The X-ray tomography imaging system was employed to visualize the fracture patterns of the specimens tested for compressive strength and aggregate distribution throughout the specimens for both normal concrete (NC) and SCC. Typical fracture patterns as provided by the standard test method give a relative sense of how strong the mix is or if there are problems with the equipment.

3. Materials and experimental procedure

3.1. Materials description

All concrete mixtures used ASTM type I portland cement and same type of river gravel and natural sand. To obtain self-consolidating concrete, three mineral admixtures blast furnace slag, fly ash and silica fume, and two chemical admixtures - a HRWR and a viscosity modifying agent were added to the mixes in various proportions. Details on the materials used to prepare the concrete cylinders are provided in the following.

3.1.1. Aggregates

The coarse aggregate used in the concrete mixtures was uncrushed river gravel, supplied from the southeastern part of Louisiana and had the maximum nominal size of 19 mm. Its absorption was 1.9% (ASTM C 127) and specific gravity of 2.45 (ASTM C 128). Also, sieve analysis was performed on the coarse aggregate according to ASTM C 136. The results presented in Table 1 are within the limits of ASTM C 33.

The fine aggregate was a clean natural rounded sand with a maximum size of 1 mm. The sand was supplied from the southern part of Louisiana, where large deposits of different types of sand exist. Its absorption and specific gravity were 1.12% and 2.63%, respectively.

3.1.2. Mineral admixtures

The mineral admixtures used in the self-consolidating concrete were: Class C fly ash complying with the requirements of ASTM C 618 and has the relative density of 2.5; Grade 100 ground granulated iron blast furnace slag, complying with the requirements of ASTM C 989 and having a specific gravity of 2.89, having moderate activity in terms of its interaction with calcium hydroxide $Ca(OH)_2$ in cement; and Powder silica fume, complying with the requirements of ASTM C 1240, containing an average of 95.7% of $SiO_{2,}$ and having the specific gravity of 2.3.

3.1.3. Chemical admixtures

The superplasticizer used was a Rheobuild 3000FC ready-to-use high range water-reducing (HRWR) admixture. This type of superplasticizer can be used to produce rheoplastic concrete that flows easily and maintains workability for long time without any effect on setting time. Rheobuild 3000FC admixture meets ASTM C494 requirements for Type F, high-range water-reducing admixture and has a recommended dosage range of 4–15 ml/kg of cementitious material for most concrete mixes. Sometimes, depending on water–cement ratios, dosages outside the recommended range may be required.

The viscosity modifying admixture (VMA) used in the study was a Rheomac UW 450 anti-washout admixture, ready-to-use, liquid, cellulose-based admixture that is specially developed for underwater concrete applications. Concrete containing Rheomac UW 450 admixture exhibits superior resistance to washout of cement and fines and is recommended for use at a dosage range of 20–130 ml/kg of cementitious material. For low water–cement ratios, dosages may be decreased.

3.2. Batching procedure and specimens preparation

All the mixtures were prepared in small – approximately 0.03 m^3 (1 ft^3) – batches following the ASTM C 192 procedure. The self-consolidating concrete mix design used in the study is based on previous work done in Japan, US, and Canada [21,28]. A total of twelve batches, one batch for each w/c ratio, were prepared for seventy-two concrete cylinders for both types of concrete, including the cylinders needed to assess the splitting tensile test after seven days of curing in the moisture storage. Ten separate batches (one for each w/c ratio) were made for the slump flow and U-tube tests. Several batches were prepared using the trial-and-error method, while adjusting the HRWR and VMA admixtures to achieve the targeted slumps and U-tube flows. The mix proportions for casting the concrete specimens are presented in Table 2. The type I portland cement was replaced by blast furnace slag (25%), fly ash (15%), and silica fume (5%). The water-to-cementitious materials ratios varied from 0.3 to 0.6 while the rest of the components were kept the same. Aggregates were maintained in damped conditions to prevent segregation. For the SCC mixtures the mixing intervals were increased by 1–2 min to allow for the chemical admixtures to disperse thoroughly.

The mix proportions for the normal concrete to prepare the required cylinders and conduct the slump tests were similar to SCC except that no mineral and chemical admixtures were used. As for SCC, same amount batches were made so that six cylinders can be cast from each batch.

No vibration or rodding were applied for any of the SCC specimens whereas appropriate vibration and rodding were applied to NC. After preparation, all specimens were stored in the moist storage facility until testing.

Table 1
Sieve analysis for the river gravel.

Sieve Size	Retained (%)	Amount passed (%)
1″ (25 mm)	0.25	99.8
¾″ (19 mm)	6.4	93.6
½″ (12.5 mm)	47.3	46.3
3/8″ (9.5 mm)	10.45	35.8
No. 4 (4.75 mm)	28.2	7.6
No. 8 (2.36 mm)	7.3	0.1
Pan	0.1	0