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Development of methodology to evaluate passing ability and test sample preparation for superworkable concrete

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HIGHLIGHTS

- Characterization using test setups adapted to fibers and medium consistency of fresh superworkable concrete with and without fibers (SWC and FR-SWC).
- Consideration of fiber type, use of VMA, slump flow, and degree of consolidation in SWC and FR-SWC to compromise between mechanical properties, surface defects, and segregation resistance.
- Estimation of mechanical consolidation energy by vibration and by rodding.
- Estimation of mechanical consolidation for unit weight, air volume, slump flow, modified J-Ring, and modified L-box tests.

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ABSTRACT

The use of superworkable concrete (SWC) and fiber-reinforced SWC (FR-SWC) necessitates some mechanical consolidation to secure proper consolidation and ensure complete filling of the formwork. This paper evaluates the extent of mechanical consolidation on the risk of segregation, surface quality, and mechanical properties of SWC and FR-SWC. In total, 10 FR-SWC mixtures were prepared using 0.5% polypropylene and steel fibers incorporated. Test parameters involved the incorporation or omission of viscosity-modifying admixture (VMA) and the addition of high-range water reducer to vary slump flow between 450 and 550 mm. The passing ability was evaluated using modified L-box and J-Ring test methods. Test cylinders were cast in one layer and underwent different degrees of mechanical consolidation using a 10-mm steel rod. A vibrating table was also used to induce high consolidation effort during 20 s and 25 s. Image analysis was carried out on longitudinally saw-cut sections along the concrete cylinders to evaluate segregation and surface defects corresponding to various consolidation modes.

Sample rodding was found to enable the reduction of surface honeycombing without affecting mechanical properties or increasing the risk of segregation. The vibration consolidation enhanced mechanical properties and surface quality but led to segregation, unless the concrete was highly stable. Recommendations were made on the adequate consolidation energy on samples and test method devices using both consolidation modes. For example, test samples can be cast in one lift and consolidated with 20 strikes of rodding or vibration for 20 s. The modified L-box with internal consolidation, using a 33-mm pencil vibrator to reach a minimum L-box blocking ratio of 0.80, of 5 and 20 s is recommended for SWC and FR-SWC, respectively. Such concrete should be cast in a single lift and consolidated with 10 internal strikes using a 16-mm steel rod when performing the slump flow, modified J-Ring test, unit weight, and air volume tests.

1. Introduction

Superworkable concrete (SWC) is a new class of high-performance concrete with adapted rheology that requires low energy of mechanical consolidation to ensure proper filling of the formwork. SWC can present some advantages over self-consolidating concrete (SCC) in terms of lower chemical admixture demand, greater robustness, lower risk of segregation, and lower formwork pressure characteristics [1]. Fiber-reinforced superworkable concrete (FR-SWC) belongs to this category of high-performance concrete with adapted rheology that can be used for

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the infrastructure construction. Compared to fiber-reinforced self-consolidating concrete (FR-SCC) that has typical slump flow values of 630–750 mm, SWC and FR-SWC have lower slump flow values of 450– 600 mm.

It is recommended to limit the volume of steel, synthetic, or hybrid fibers in SCC to 0.5%, by volume, to ensure adequate self-consolidating characteristics [2]. Greater volumes of fibers (V_f) needed to increase tensile strength, ductility, and resistance to cracking can hinder self-consolidation properties, yet such greater volume of fibers can be accommodated in FR-SWC since the mixture is subjected to some mechanical consolidation. FR-SWC with V_f of 0.75%, can be produced with low risk of blockage and segregation when the concrete mixture design is highly stable, such as the case when incorporating a viscosity-modifying admixture (VMA) [2]. However, the increase in fiber content in SWC can hinder workability, thus necessitating greater consolidation energy to ensure proper performance. Excessive mechanical consolidation, however, can lead to segregation and surface defects, thus impacting performance. This issue of consolidation energy is also important when preparing test specimens to evaluate mechanical properties of SWC and FR-SWC as well as the filling of test apparatuses for determining the workability of such concrete. For example, the slump flow test of SCC involves the filling of the slump cone in one lift without any consolidation; such protocol may not be suitable for casting SWC and FR-SWC. The same protocol for filling the test apparatus applies for the testing of the passing ability of such concrete materials.

This paper investigates ways to modify the J-Ring and L-box test methods that can enable better assessment of the passing ability of SWC and FR-SWC. The study also seeks to develop a consolidation protocol for SWC and FR-SWC that can secure adequate consolidation without segregation and surface defects. Such consolidation and test protocols are intended for use during sample preparation to evaluate fresh and hardened properties of such concrete. This includes the determination of unit weight, air volume, slump flow, J-Ring flow, and, L-box blocking passing ability, as well as samples to determine mechanical properties. The study also involves the evaluation of the effect of VMA, used to modify the viscosity of SWC and FR-SWC, and the extent of mechanical consolidation on concrete surface quality, segregation, and mechanical properties.

2. Experimental investigation

2.1. Materials and mixture proportioning

Continuously-graded natural sand with a fineness modulus of 2.6 and a crushed limestone aggregate with a nominal maximum aggregate size of 10 mm were used. The coarse aggregate and sand had specific gravities of 2.73 and 2.66, respectively, and water absorption values of 0.52% and 0.97%, respectively. Ternary cement (GUb-S/SF) containing approximately 70% Type GU cement, 25% granulated blast furnace slag, and 5% silica fume, by mass of binder, was used. A polynaphthalene sulfonate-based high-range water-reducer admixture (HRWRA), a synthetic resin-type air-entraining admixture (AEA), and a liquid-based VMA were used. The latter is based on polysaccharide biogum.

Two types of fibers were used: kinked multifilament synthetic fibers (MU) and hooked-end steel fibers (ST). The fibers are 50 and 30 mm in length, 0.67 and 0.55 mm in equivalent diameter, with aspect ratios of 74 and 55, tensile strengths of 575 and 1300 MPa, and specific gravities of 0.92 and 7.85, respectively.

The mixture proportions of the investigated concretes are given in Table 1. The FR-SWC mixtures were proportioned following a method proposed by Khayat et al. [2], which was principally developed for proportioning of FR-SCC. The SWC mixtures with the designations MU or ST refer to the type of fibers. The 450 and 550 designations refer to the targeted slump flow levels of 450 mm and 550 mm, respectively. VMA (if any) refers to mixture prepared with VMA. The number 0, 5, 10, 15, or 20 refers to the number of strikes applied for the consolidation of the concrete. The numbers 20T and 25T refer to 20 and 25 s of consolidation on a vibrating table.

The concrete mixtures were prepared using a 110-liter capacity drum mixer rotating at 20 rpm. The fibers (ST and MU), fine and coarse aggregates, half of the mixing water cooled to approximately 17 °C, and AEA were mixed first for 1 min. For the case of the fibrillated and lightweight MU fibers, the fibers were mixed with the coarse aggregates and sand for 4 min before adding the water and AEA in order to break down the fibrillates. This was done to avoid alteration of the AEA efficiency due to the excessive mixing duration and its effect on air volume. The ternary cement was then added, followed by the remaining water and HRWRA and mixed for 1 min. The liquid-based VMA was introduced, and the concrete was mixed for 3 min to obtain sufficient flowability and stability. The mixing was stopped for 2 min. The concrete was remixed for 2 min. The same mixing procedure was applied for the non-fibrous SWC.

2.2. Test procedures

2.2.1. Deformability and passing ability

In the fresh state, the SWC and FR-SWC were tested to evaluate the slump flow, T_{400} spread time, and visual stability index (VSI). The T_{400} was determined instead of the T_{500} [3] that is used for mixtures of self-consolidating consistencies given the fact that SWC may not achieve a spread of 500 mm.

The passing ability was evaluated using the modified J-Ring [2] and modified L-box test methods. The clearance between the bars in the J-Ring and L-box setups were set to correspond to at least 2.5 times of fiber length (L_f) in order to prevent blockage of the

Table 1
Mixture proportions of SWC mixtures.

Mixture	Content (kg/m³)					Dosage (ml/m³)			Slump flow (mm)
	Water	Ternary cement	Sand	10-mm MSA	Fiber	HRWRA	VMA	AEA	
SWC-450	200	475	783	791	0	3620	–	190	450
SWC-550						4760			550
MU-450			849	711	4.6	4630	–		440
MU-550						4760			550
MU-450-VMA						5710	230		450
MU-550-VMA						5910			550
ST-450			811	750	39.3	4670	–		450
ST-550						5050			560
ST-450-VMA						4760	230		460
ST-550-VMA						5710			550